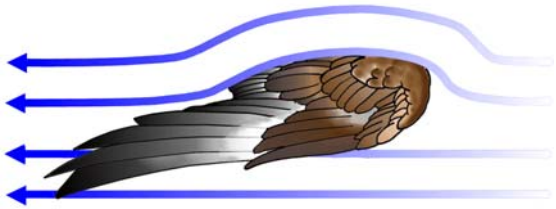
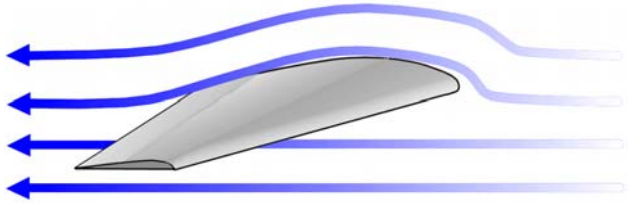
Investigation of Stability Issues for an Adaptive Trailing Edge System





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Results from the ADAPWING2 project funded by Danish Research Council

Outline

- Motivation - Why?
- Theory – How?
  - Aerodynamic model
  - Structural model
  - Control
  - Time lag
  - Coupling
- Validation
- Results
- Conclusion

Motivation

- State of the art active load reduction employs pitching of whole wing
- But… Very long flexible blades may keep us from pitching fast enough to reduce fatigue loads more than approx 20%

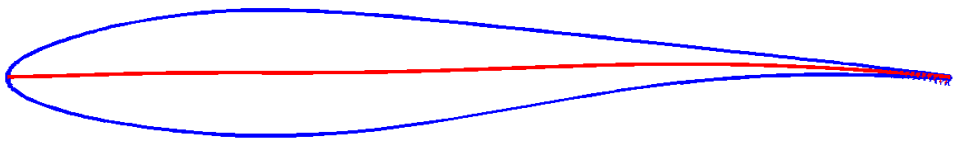
- What if much faster load control could be possible?
- What if local load control on the blade could be possible?

- Solution: Adaptive Trailing Edge Geometry

Motivation

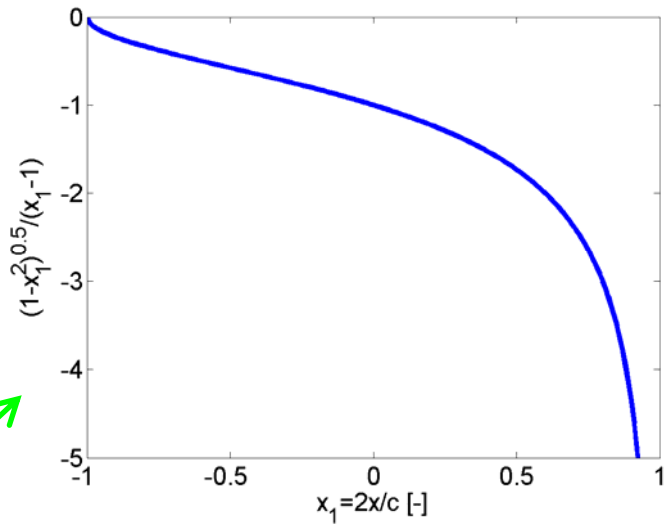
But why at the trailing edge?

- Potential thin-airfoil theory:



#1: Maximize bang for bucks

$$C_L = 2\int_{-1}^{1} \frac{\partial y}{\partial x}(x_1)\,\frac{\sqrt{1-x_1^{\,2}}}{x_1-1}\,dx_1$$

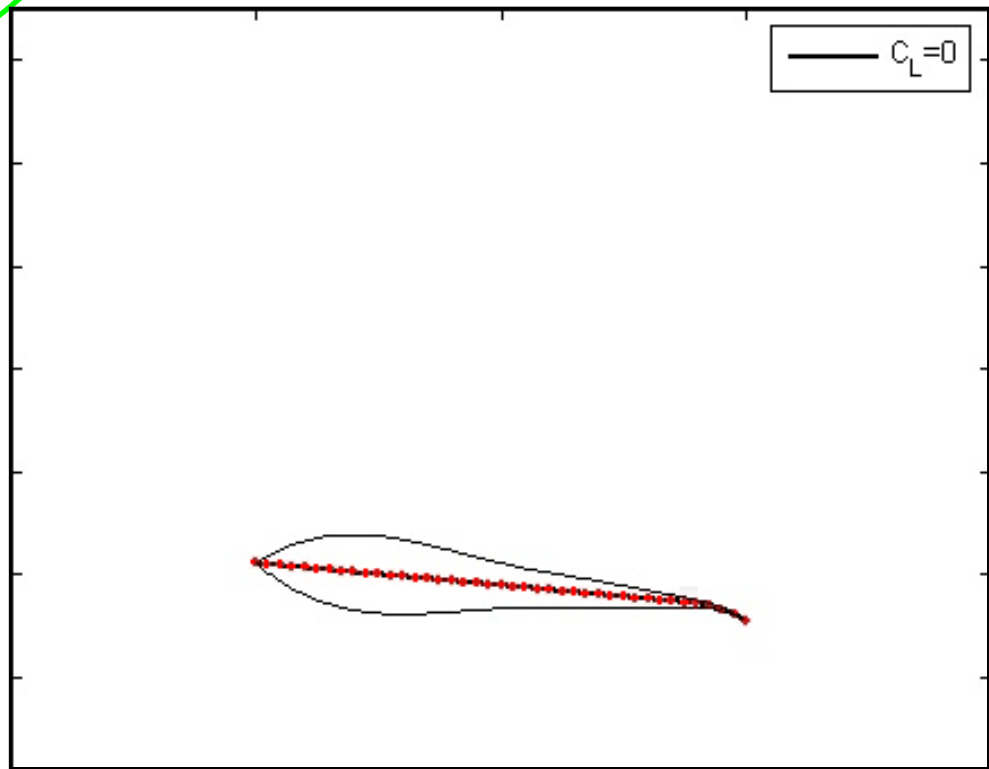


#2: Low loads at TE…

Both steady and unsteady

DynamicLoads.mpg

Click data plot at right to play video.



Motivation

..And why not just a rigid flap?

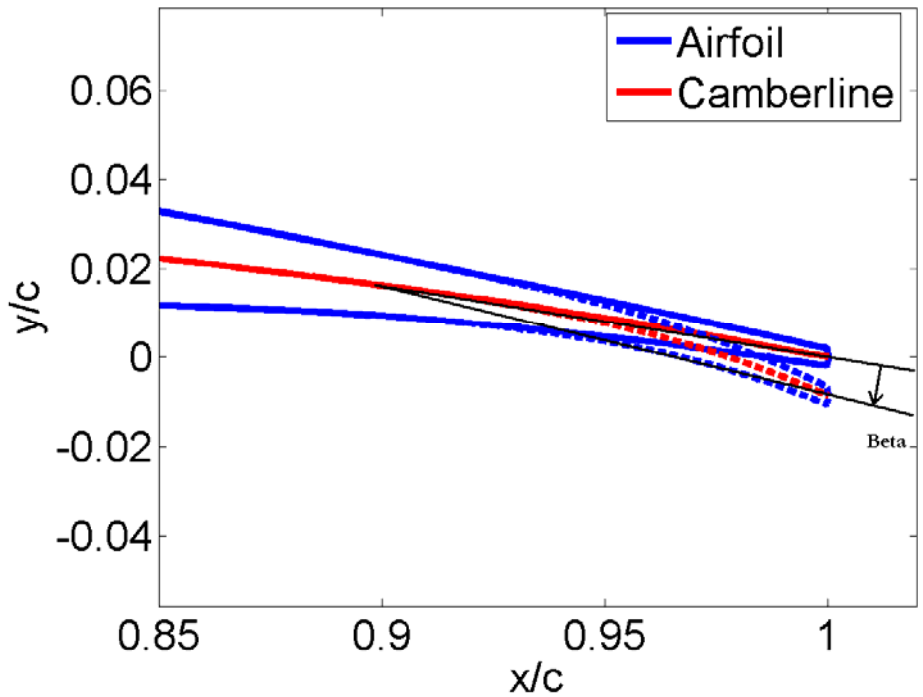
- Surface discontinuity triggers stall

⇓

- Noise issues
- Bad L/D leading to loss in power production
- Flap losing it's potential load reducing effect

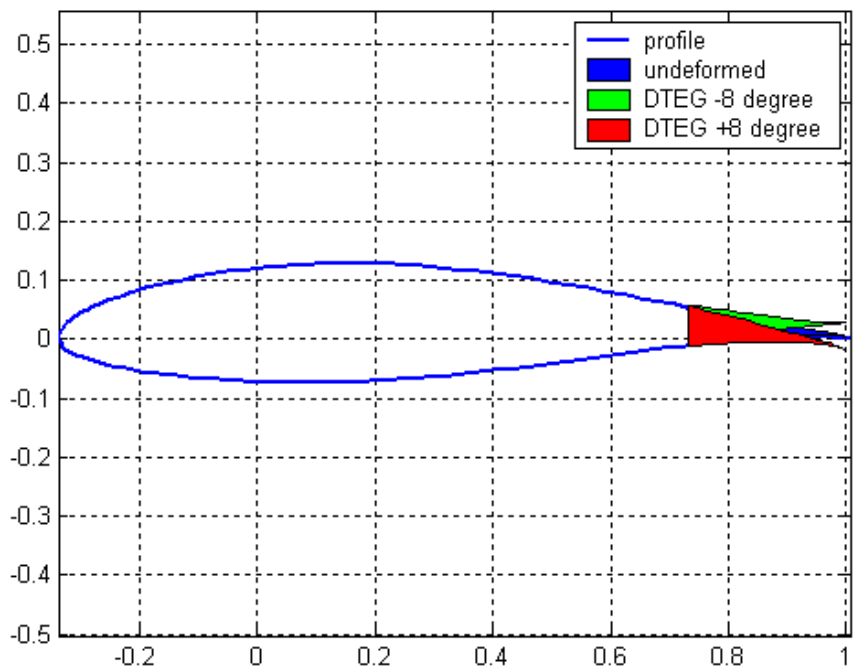
⇓

- Go for the continuously deforming one (smooth deformation shape)!



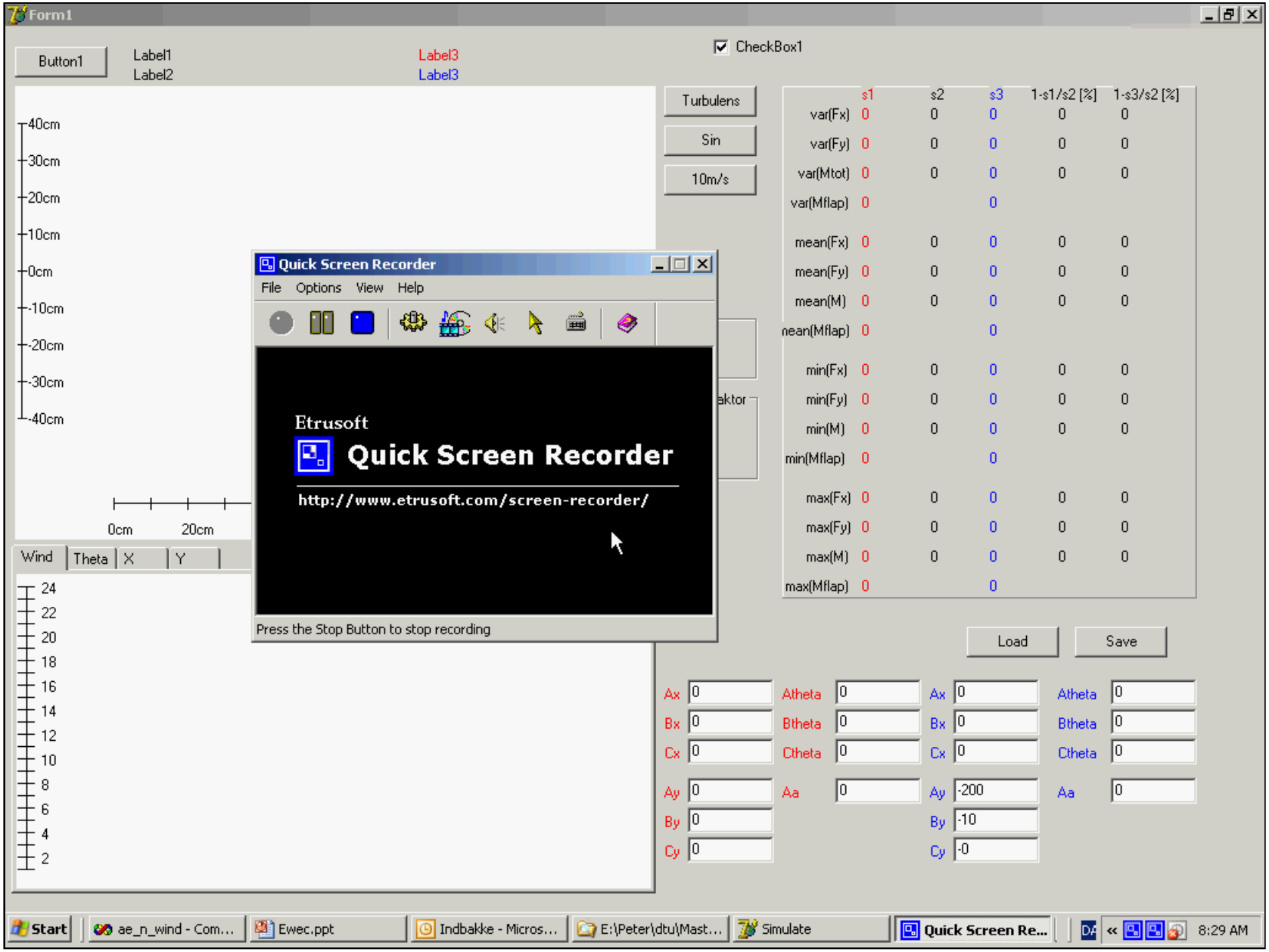
Motivation

- Previous computations has shown big fatigue load reduction potential employing this idea (2D.avi)



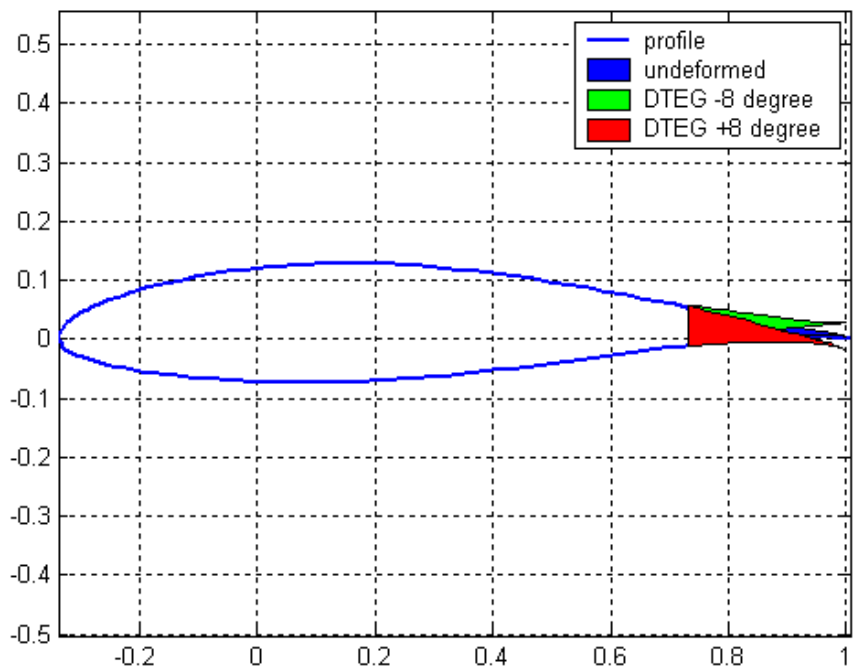
Motivation

(Click image below to play video)



Motivation

- Previous computations has shown big fatigue load reduction potential employing this idea (2D.avi)
- Furthermore: 2D simulations show same trends as much more time consuming and complex 3D simulations
- **But what happens to the stability of such a system?**

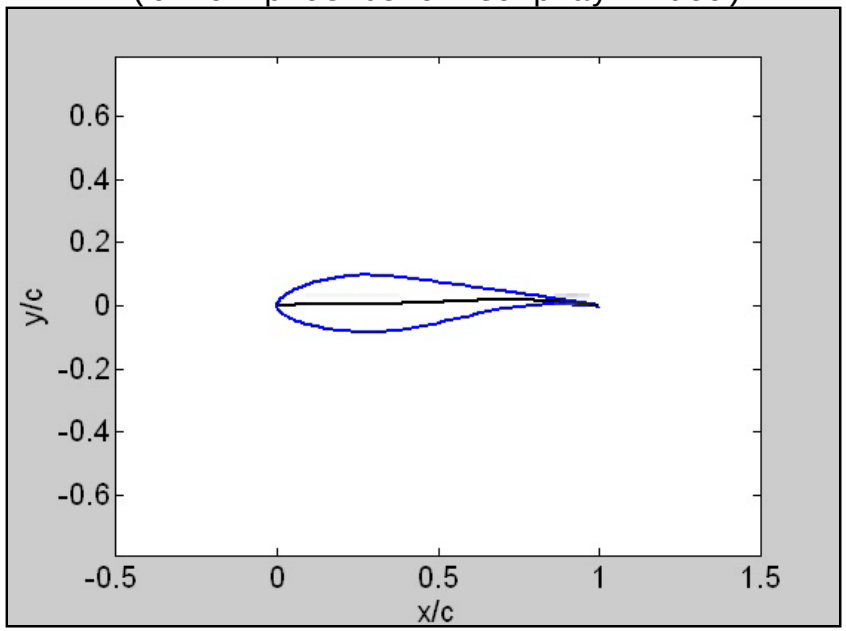


Motivation

- Preliminary computations using a time-stepping tool

Classical flutter

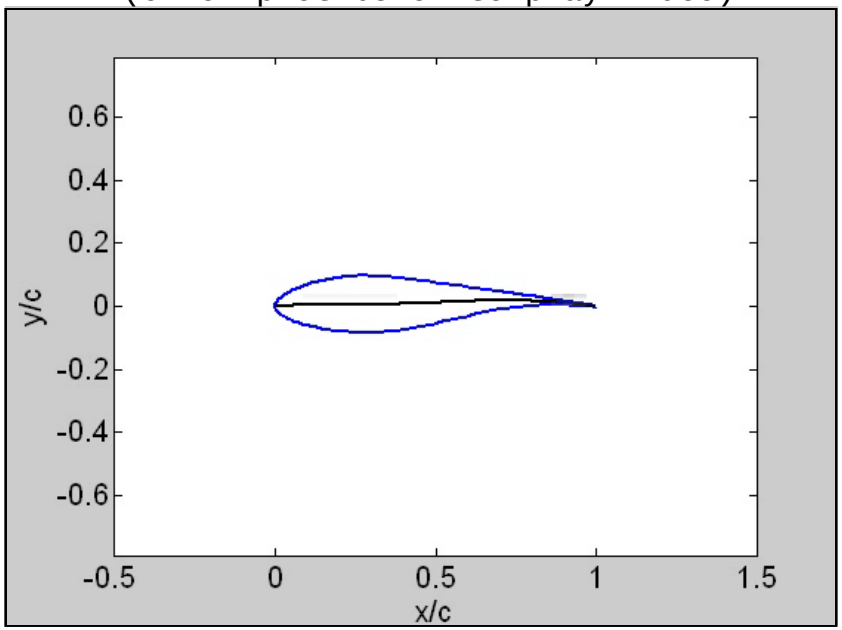
(Click plot below to play video)



142 m/s

"Control flutter"

(Click plot below to play video)



90 m/s

- But how can we solve a problem like this?

Theory

Returning to simple modelling again to capture the essence of the problem:

- 2D
- Unsteady potential flow thin-airfoil aerodynamics
- Simple mass spring damper model for heave and pitch DOF
- Generalised deformations for TE DOF
- Simple control algorithm
- First order filter to simulate time lag in control

Theory: Aerodynamics

Unsteady potential-flow thin airfoil approximation:

- Reduce the airfoil to zero thickness camber-line
- Neglect viscous effects
- Enforce no flow through camberline
- Use indicial function approximation for memory effect of the wake

$$\Downarrow$$

Theory: Aerodynamics

$$
\begin{aligned}
Q &= (V-\dot{X})\alpha - \dot{Y} + (1/2-a)b\dot{\alpha} \\
&\quad -\frac{1}{2\pi}\left(V-\dot{X}(t)\right)\sum_{i=1}^{Ndefl} Defl_i(t)H_{dyd\varepsilon,i} \\
&\quad -\frac{1}{2\pi}\sum_{i=1}^{Ndefl} D\dot{e}fl_i(t)H_{y,i}
\end{aligned}
$$

$$
\begin{aligned}
Q\mathbf{C} &= Q(t)\left(1-\sum_i A_i\right)+\sum_i z_i \\
\dot{z}_i + b_i\frac{1}{b}(V-\dot{X}(t))z_i &= b_iA_i\frac{1}{b}(V-\dot{X}(t))Q(t).
\end{aligned}
$$

$$
\begin{aligned}
N &= \rho b^2\pi\left(-\ddot{X}\alpha + (V-\dot{X})\dot{\alpha} - \ddot{Y} - ab\ddot{\alpha}\right) \\
&\quad +\frac{\rho b^2}{\pi}\sum_{i=1}^{Ndefl}\Big(D\ddot{e}fl_i(t)F_{y,i}(-1) - \ddot{X}Defl_i(t)F_{dyd\varepsilon,i}(-1) \\
&\qquad +(V-\dot{X})D\dot{e}fl_i(t)F_{dyd\varepsilon,i}(-1)\Big) \\
&\quad +2\pi\rho b(V-\dot{X})\cdot Q\mathbf{C}
\end{aligned}
$$

Theory: Aerodynamics

$$
\begin{aligned}
M \quad = \quad & \rho\pi(-1/8-a^2)b^4\ddot{\alpha} - \pi b^3\rho(V-\dot{X})(1/2-a)\dot{\alpha} - \rho\pi b^3 a\ddot{X}\alpha - \rho\pi a b^3\ddot{Y} \\
& +\rho b^3\frac{1}{\pi}\ddot{X}(t)\sum_{i=1}^{Ndefl} Defl_i(t)\left(G_{dyd\varepsilon,i}(-1) - aF_{dyd\varepsilon,i}(-1)\right) \\
& +\rho b^2\frac{1}{\pi}(V-\dot{X}(t))^2\sum_{i=1}^{Ndefl} Defl_i(t)F_{dyd\varepsilon,i}(-1) \\
& +\rho b^2(V-\dot{X}(t))^2\frac{1}{2}\sum_{i=1}^{Ndefl} Defl_i H_{dyd\varepsilon,i} \\
& -\rho b^3\frac{1}{\pi}(V-\dot{X}(t))\sum_{i=1}^{Ndefl} \dot{Defl}_i(t)(G_{dyd\varepsilon,i}(-1) - aF_{dyd\varepsilon,i}(-1)) \\
& +\rho b^2\frac{1}{\pi}(V-\dot{X}(t))\sum_{i=1}^{Ndefl} \dot{Defl}_i(t)F_{y,i}(-1) \\
& +\rho b^2(V-\dot{X}(t))\frac{1}{2}\sum_{i=1}^{Ndefl} \dot{Defl}_i(t)H_{y,i} \\
& -\rho b^3\frac{1}{\pi}\sum_{i=1}^{Ndefl} \ddot{Defl}_i(t)(G_{y,i}(-1) - aF_{y,i}(-1)) \qquad \text{(B.4)} \\
& +2\pi\rho b^2(V-\dot{X}(t))(1/2+a)Q\mathbf{C}
\end{aligned}
$$

Theory: Aerodynamics

$$
\begin{aligned}
\int_{-b}^{b} y_i \Delta P(\varepsilon/b)dx \quad = \quad & 2\rho\left(-\ddot{X}\alpha + (V-\dot{X})\dot{\alpha} - \ddot{Y} - ab\ddot{\alpha}\right) PI1_i \\
& +\rho b\frac{1}{\pi}\Bigg(\sum_{j=1}^{Ndefl} D\ddot{e}fl_j(t)PI2_{i,j} \\
& \qquad -\ddot{X}(t)\sum_{j=1}^{Ndefl} Defl_j(t)PI3_{i,j} \\
& \qquad +(V-\dot{X}(t))\sum_{j=1}^{Ndefl} D\dot{e}fl_j(t)PI3_{i,j}\Bigg) \\
& +\rho b^2\ddot{\alpha}PI4_i - 2\rho(V-\dot{X}(t))Q\mathbf{C}PI5_i \\
& -2\rho(V-\dot{X}(t))\Bigg(\frac{b}{2}\dot{\alpha}PI6_i \\
& \qquad +\frac{(V-\dot{X}(t))}{2\pi}\sum_{j=1}^{Ndefl} Defl_j(t)H_{dyd\varepsilon,j}PI7_i \\
& \qquad -\frac{(V-\dot{X}(t))}{2\pi}\sum_{j=1}^{Ndefl} Defl_j(t)PI8_{i,j} \\
& \qquad +\frac{1}{2\pi}\sum_{j=1}^{Ndefl} D\dot{e}fl_j(t)H_{y,j}PI7_i \\
& \qquad -\frac{1}{2\pi}\sum_{j=1}^{Ndefl} D\dot{e}fl_j(t)PI9_{i,j}\Bigg) \qquad (139)
\end{aligned}
$$

Theory: Aerodynamics

This looks nasty, but in its essence this can be written as

$$\underline{F}_{Aero} = \underline{f}_{A1}(\alpha, \dot{\alpha}, \ddot{\alpha}, \dot{Y}, \ddot{Y}, \beta, \dot{\beta}, \ddot{\beta}) + \underline{f}_{A2}(\underline{z}_A)$$

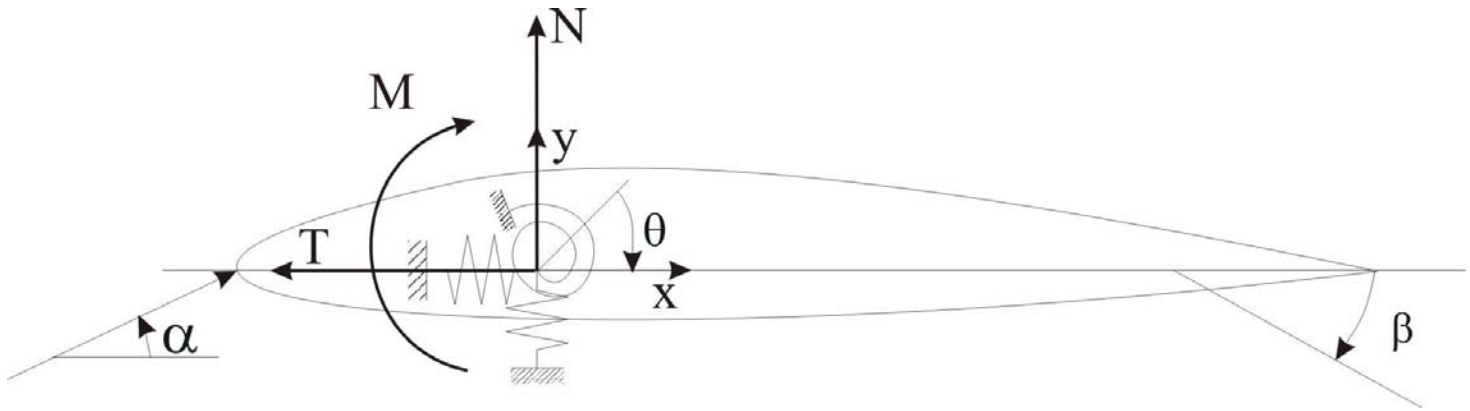
$$\dot{z}_{Ai} + b_i \, {}^{2}\!/_{c} \, V z_{Ai} = b_i A_i \, {}^{2}\!/_{c} \, VQ$$

$$Q = \alpha_{3/4} - f_{A3}(\beta, \dot{\beta})$$

This is a linear system

Theory: Structural model

Simple mass-spring-damper system for heave and pitching DOF



Generalized inertial forces and to and from the TE deformation

After linearization (small aoa approx.), this set of equations is also a linear system

Theory: Control Algorithm

Simple control algorithm:

$$\beta = \overbrace{(y - y_i) \cdot A_y}^{\text{Position}} + \overbrace{\dot{y} \cdot B_y}^{\text{Velocity}}$$
$$\underbrace{+A_\alpha \left(\frac{2\pi}{H_{dydx}} (\arctan(V_y/V_x) + \Theta_0 + \Theta - \dot{y}/V_x - \alpha_i) + \beta_i \right)}_{\text{Angle of attack}}$$

$$y_i = \underbrace{\frac{1}{\Delta T_y} \int_{t-\Delta T_y}^{t}}_{\text{Averaging window}} y(\tau) d\tau$$

For long integration times relative to the oscillations, the integral values may be disregarded, and the control becomes linear

Theory: Time lag

Time lag is modelled by:

$$\dot{\beta} + b_{Lag}\beta = b_{Lag}\beta_{Ctrl}$$

where

$$b_{Lag} = -\ln(1/2)/t_{1/2}$$

This is also a linear equation

Theory: Linking it all together

Everything is on state-space form, and can be written as

$$\underline{\underline{\mathbf{M}}}\,\underline{\ddot{\mathbf{d}}} + \underline{\underline{\mathbf{C}}}\,\underline{\dot{\mathbf{d}}} + \underline{\underline{\mathbf{K}}}\,\underline{\mathbf{d}} \quad = \quad \underline{\mathbf{0}}$$

Or, with an extended variable

$$\underline{\dot{\tilde{\mathbf{d}}}} \quad = \quad \underline{\underline{\mathbf{A}}}\,\underline{\tilde{\mathbf{d}}}$$

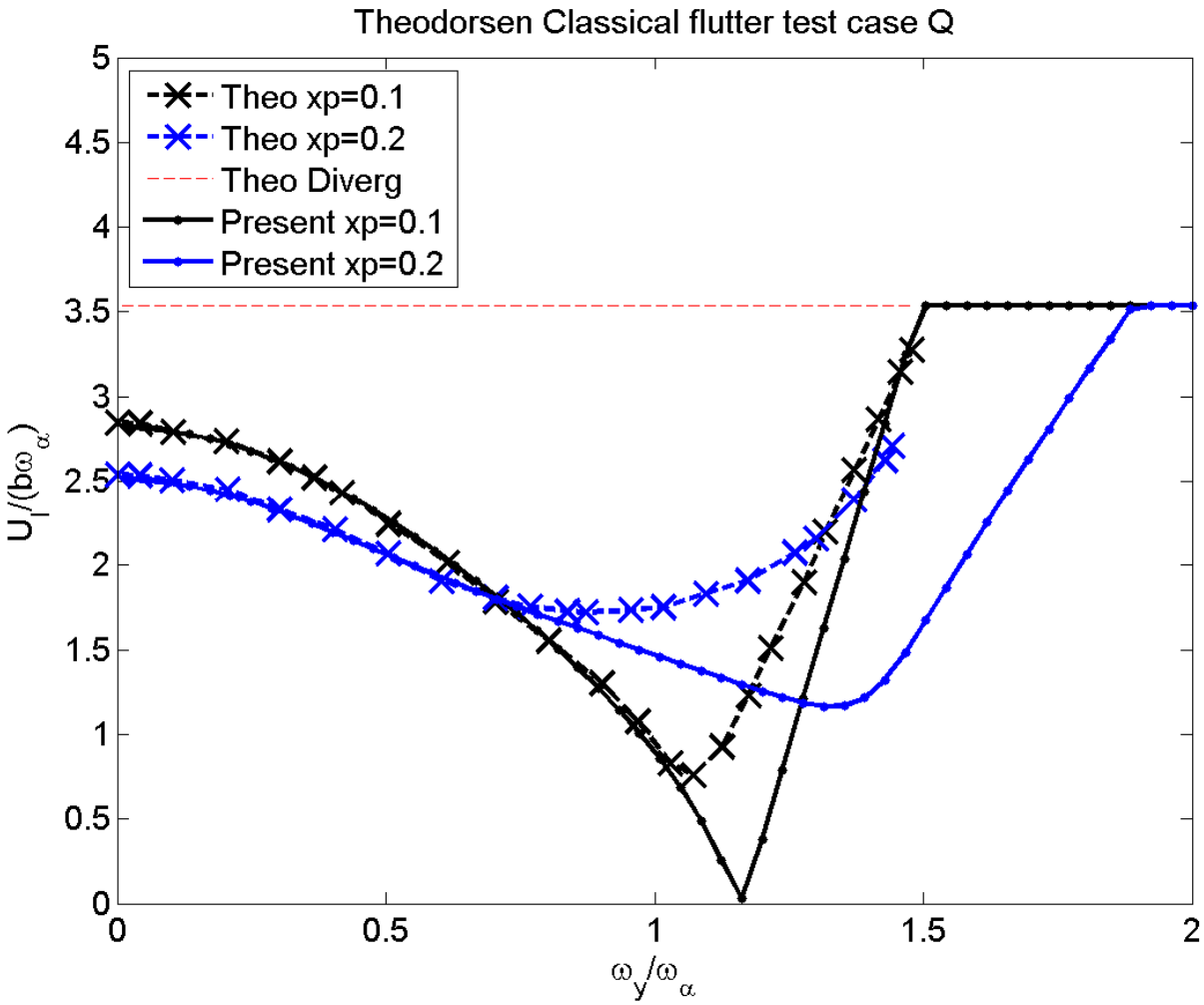
Under the approximation of harmonic oscillations, stability is determined by $det\left(\underline{\underline{\mathbf{A}}} - \lambda\underline{\underline{\mathbf{I}}}\right) \quad = \quad 0$, which is a standard eigenvalue problem

The system is stable if the greatest real part of the eigenvalues is negative

Validation

Classical flutter case: Heave and AOA

Compare with results of the classical paper of Theodorsen and Garrick



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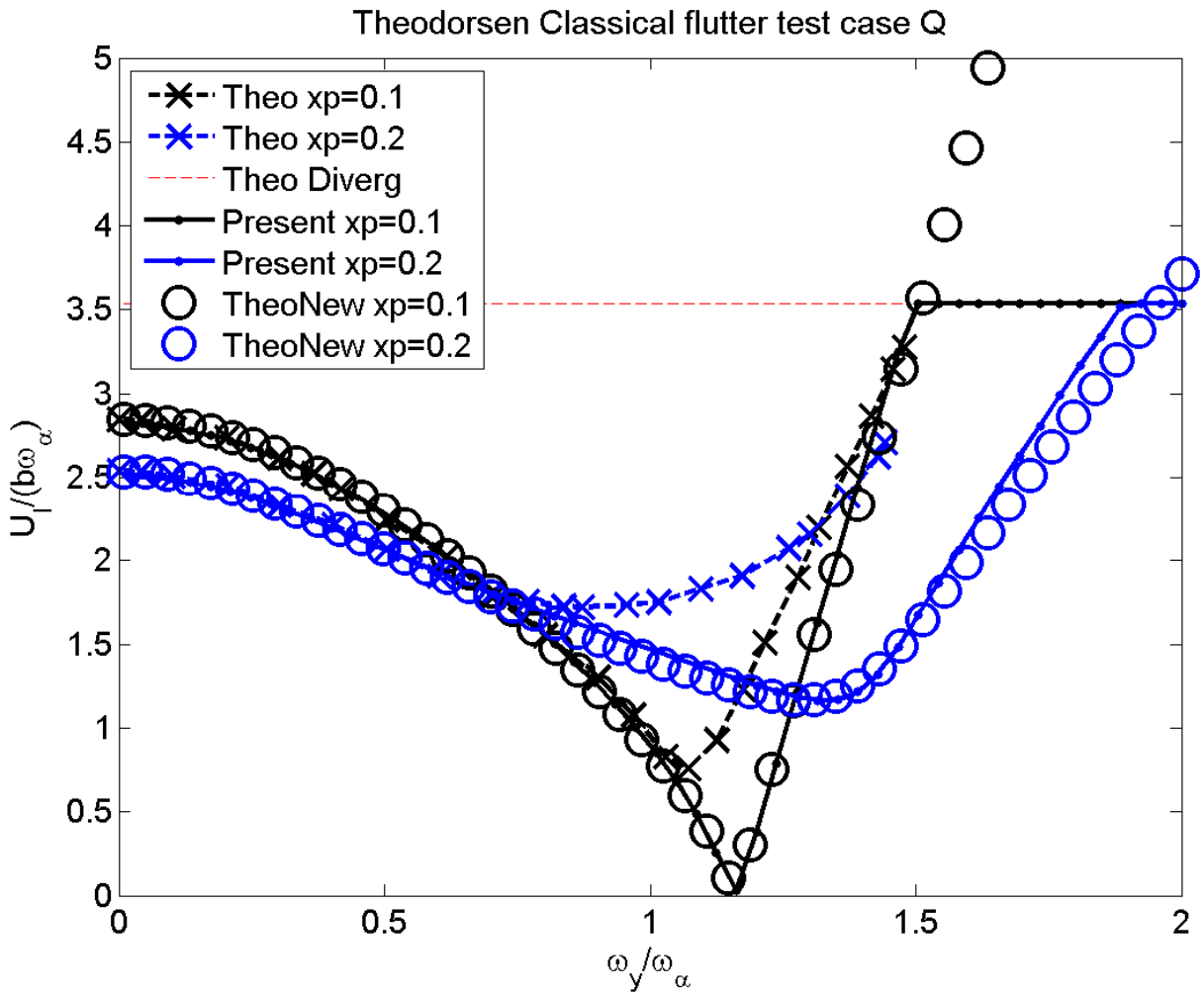
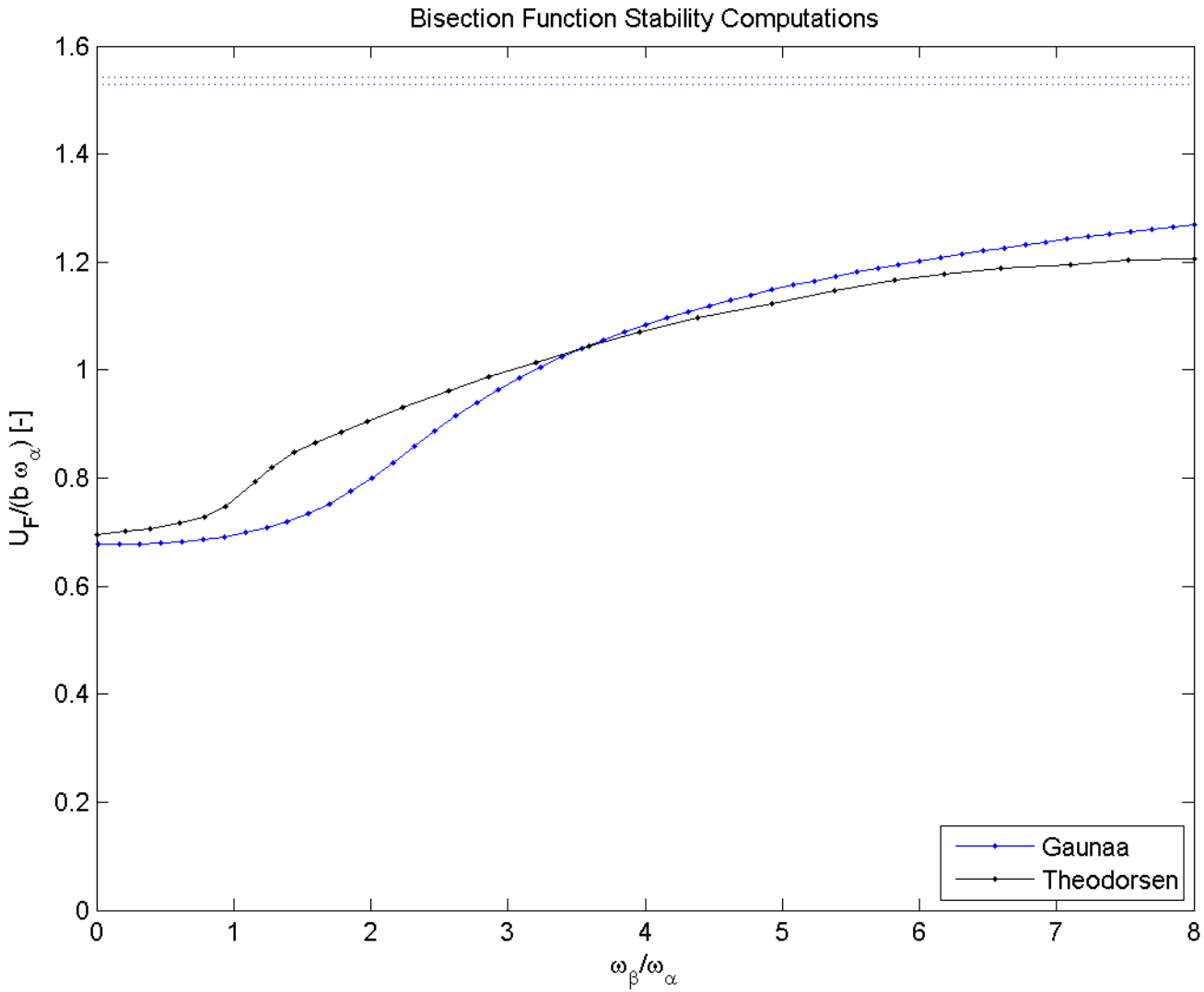


Full case: 3 DOF



Validation

Hereby validated!

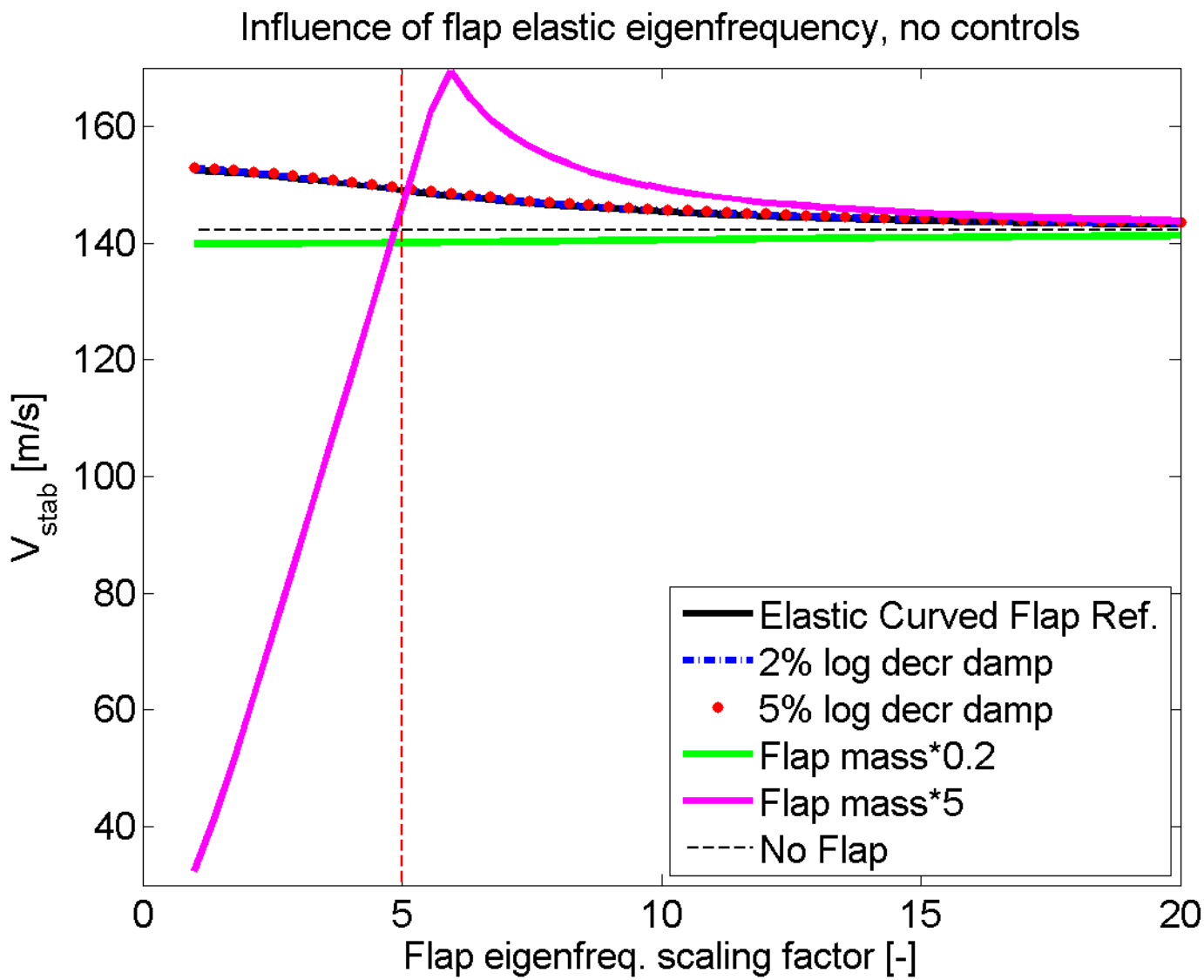
Baseline case: ”Representative 2D section”

Description	unit	value
Chord-length	m	1.0
Position of elastic axis from LE	m	0.3
Position of CG from LE	m	0.35
Total mass of airfoil per unit depth	kg	40
Intertial moment around CG		2.0
Eigen-freq. in heave direction	Hz	1.0
Eigen-freq. in pitching direction	Hz	10.0
Linear damping in the heave direction		0
Linear damping in the pitching direction		0
Proportional Control Constant		-400
Differential Control Constant		-25
Control time lag reaction half-time, $t_{1/2}$	s	0.0
Air density	Kg/m^3	1.225

Same values as Buhl et.al’s load reduction paper from Journal of Solar Engineering

Results

Variations around a baseline case corr to a WT section



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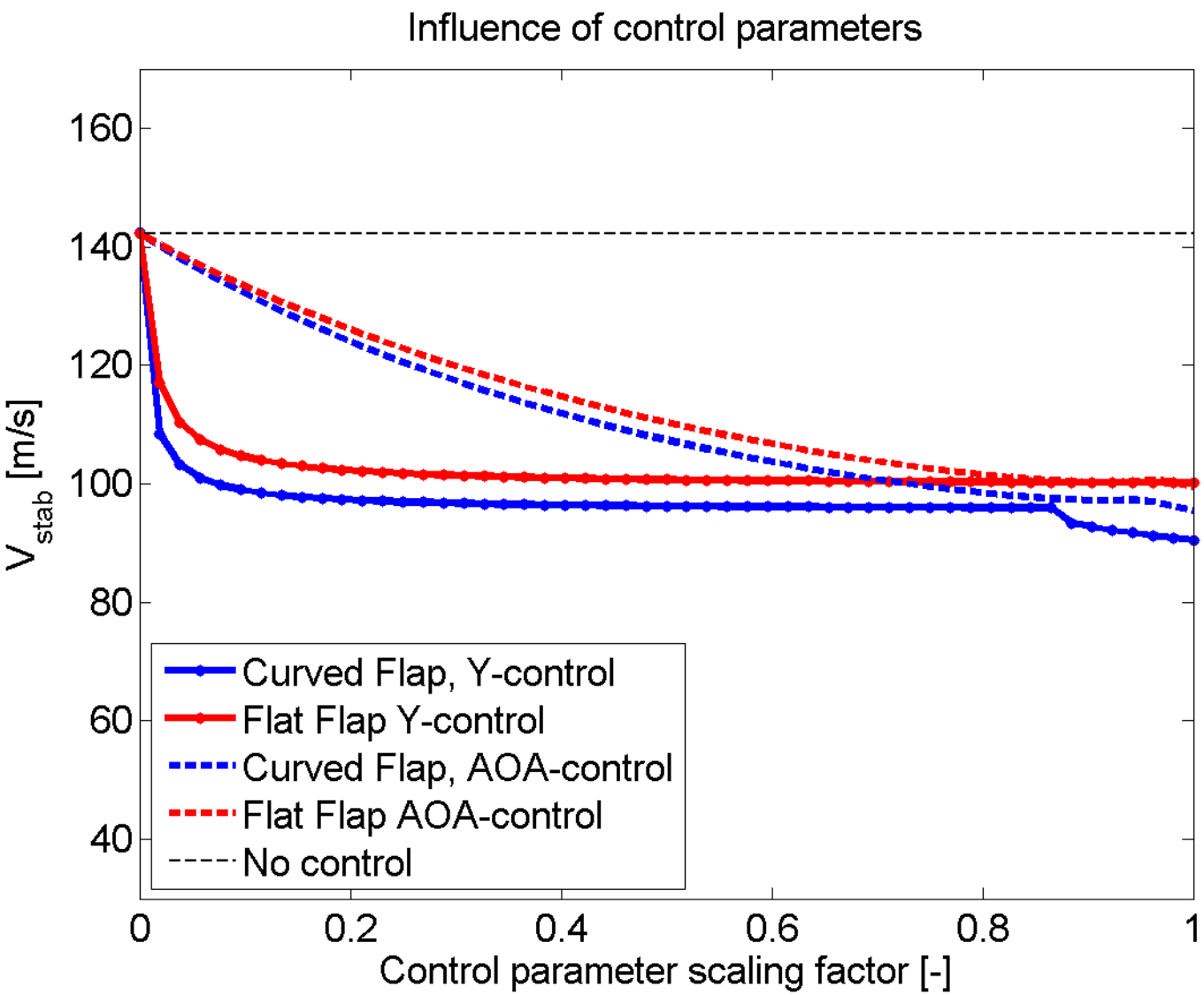

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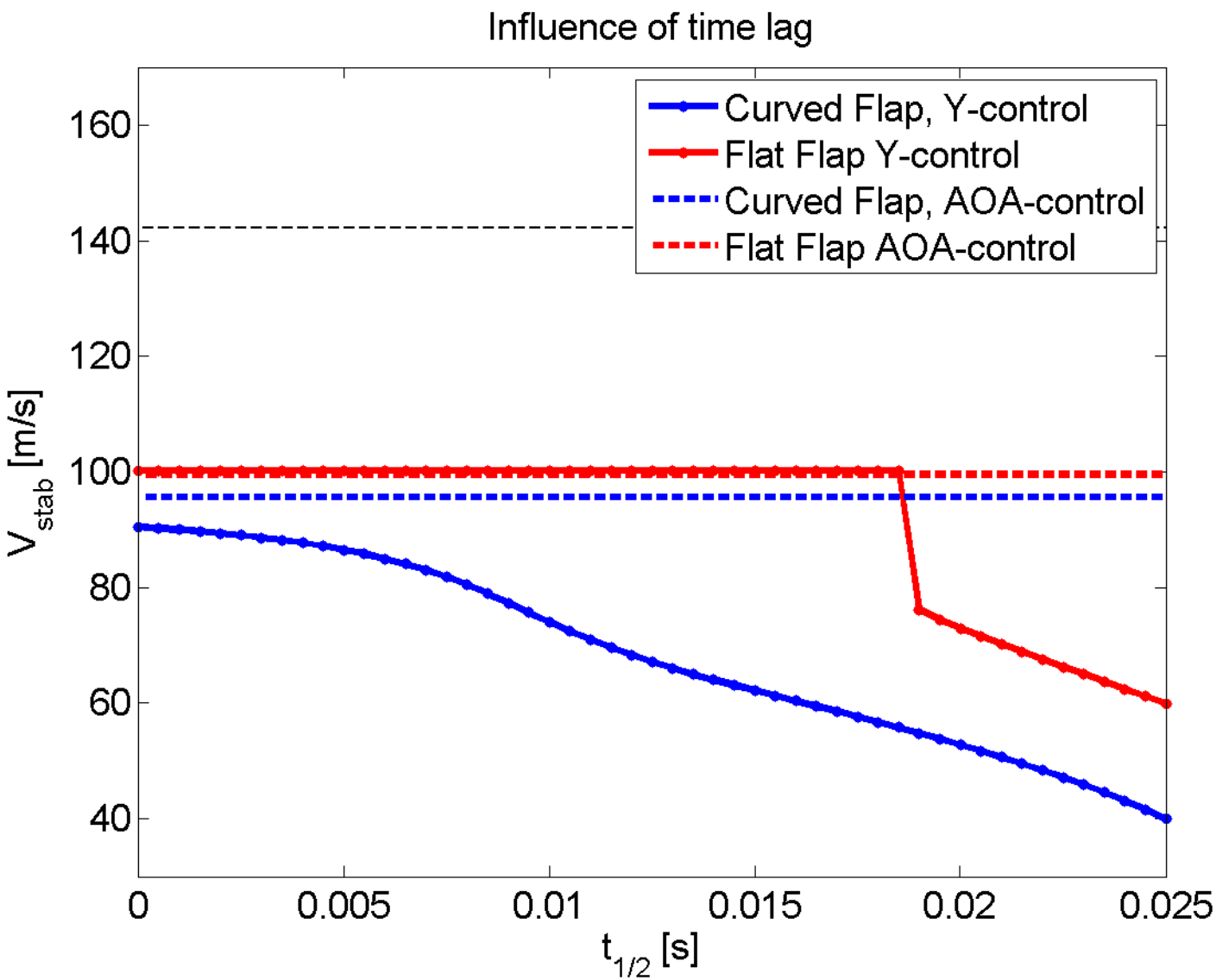

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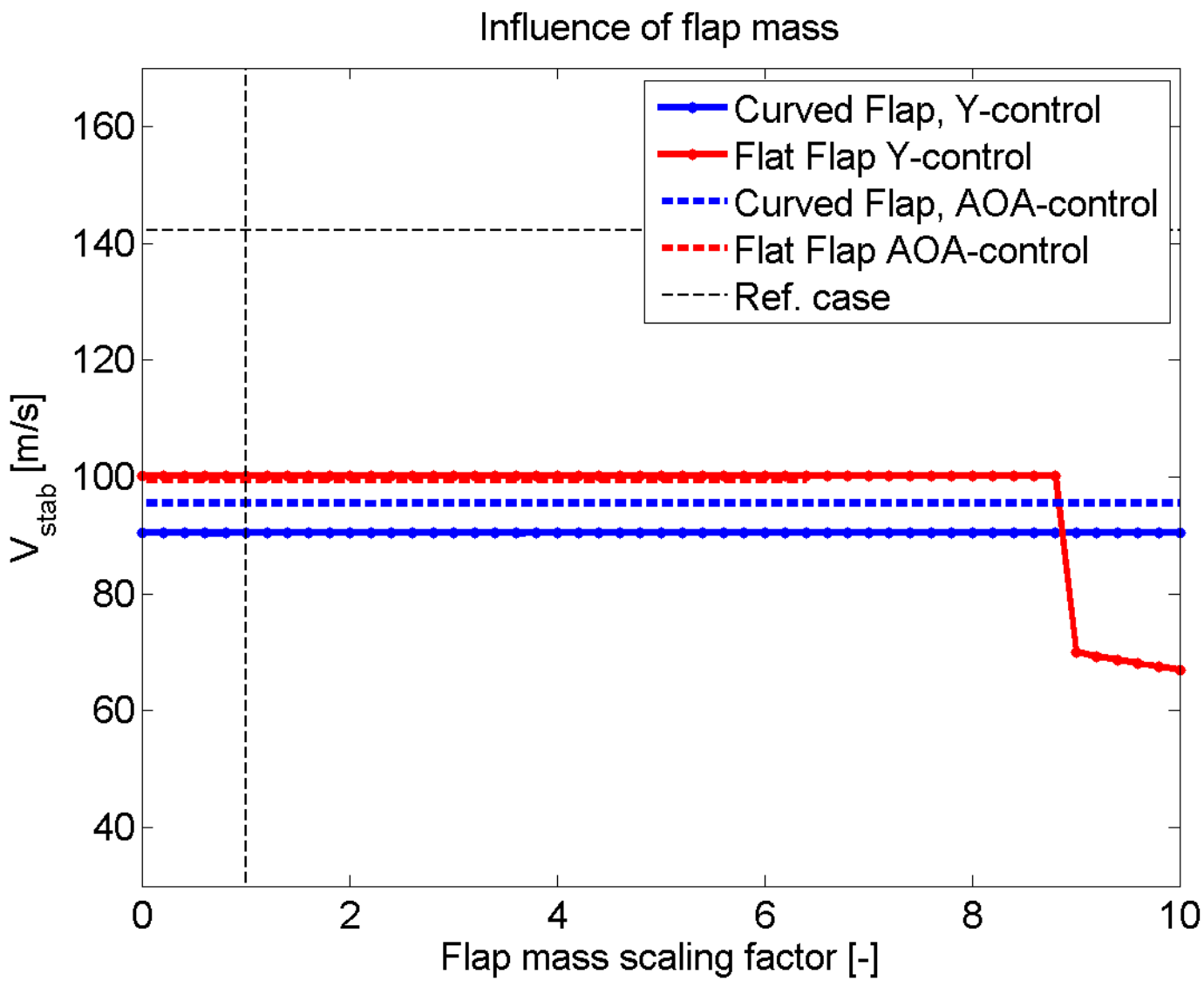

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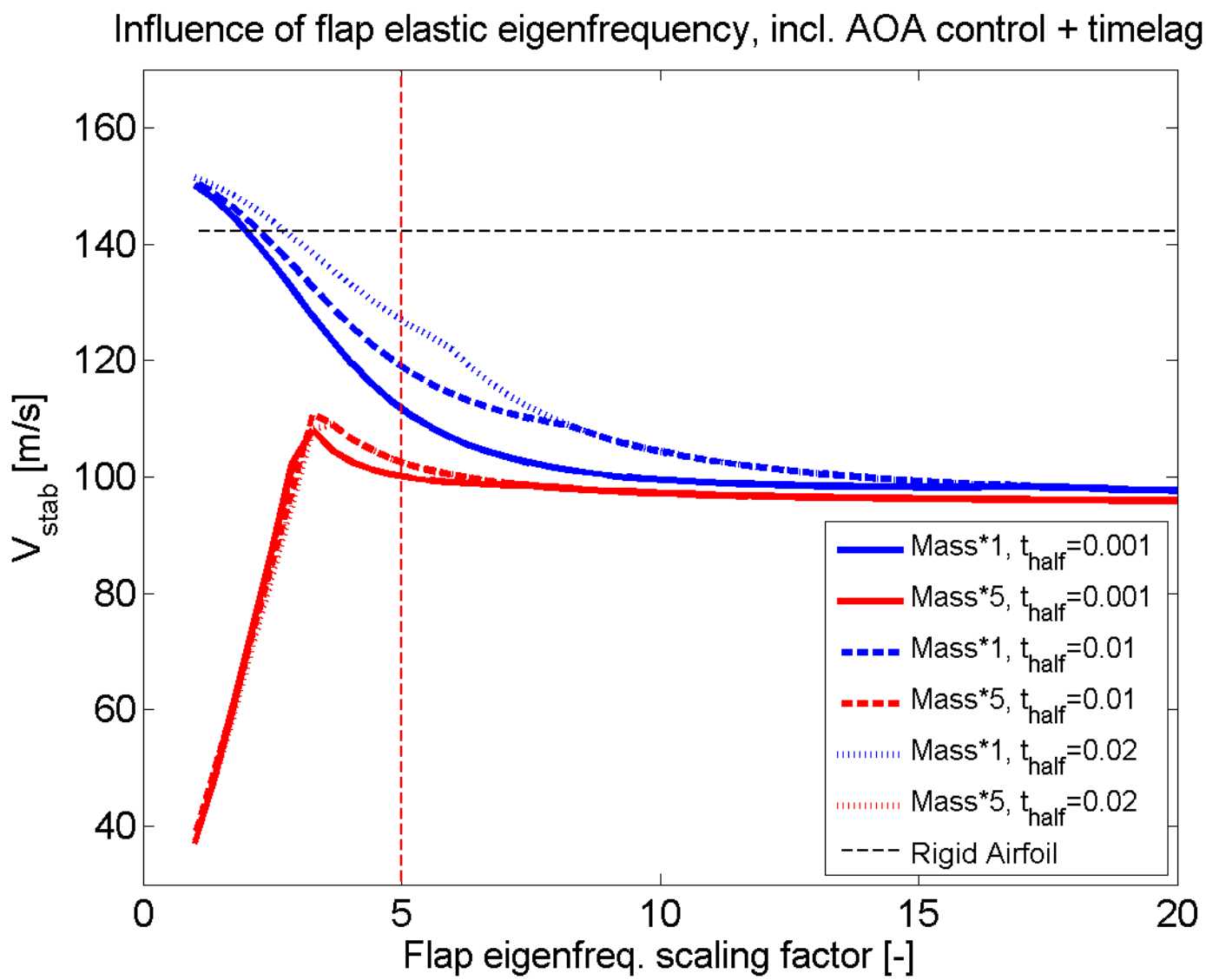

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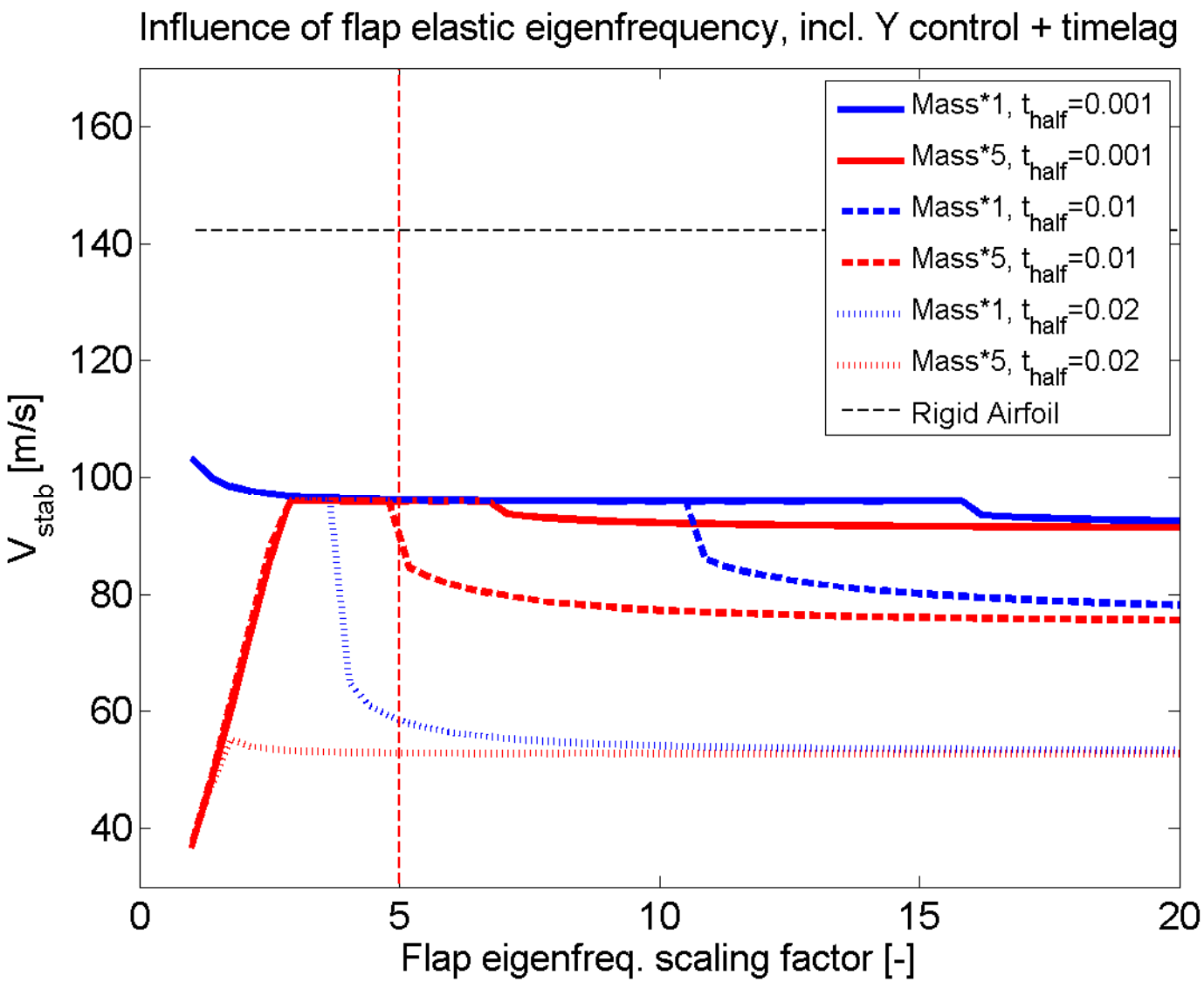
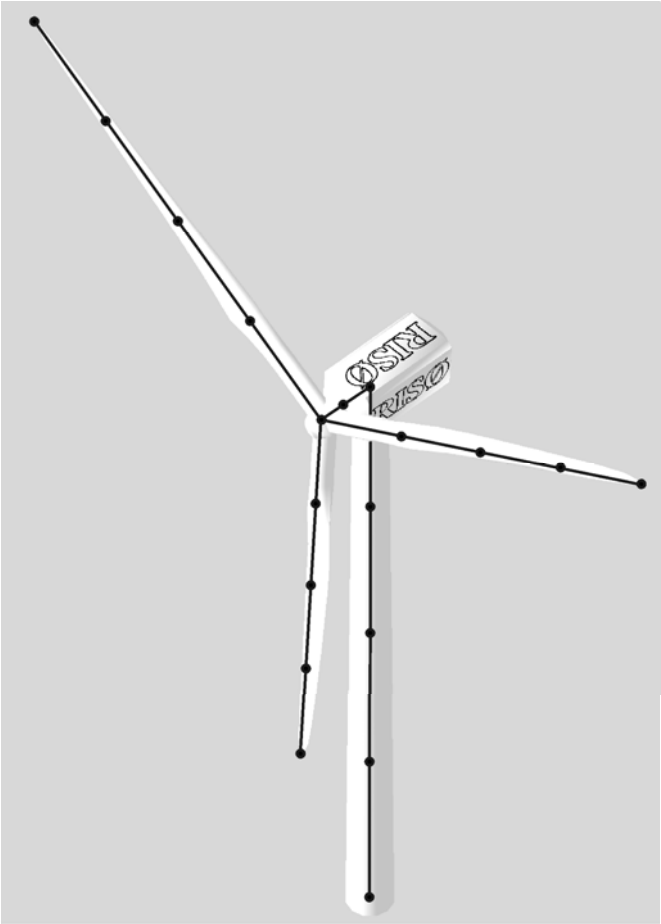
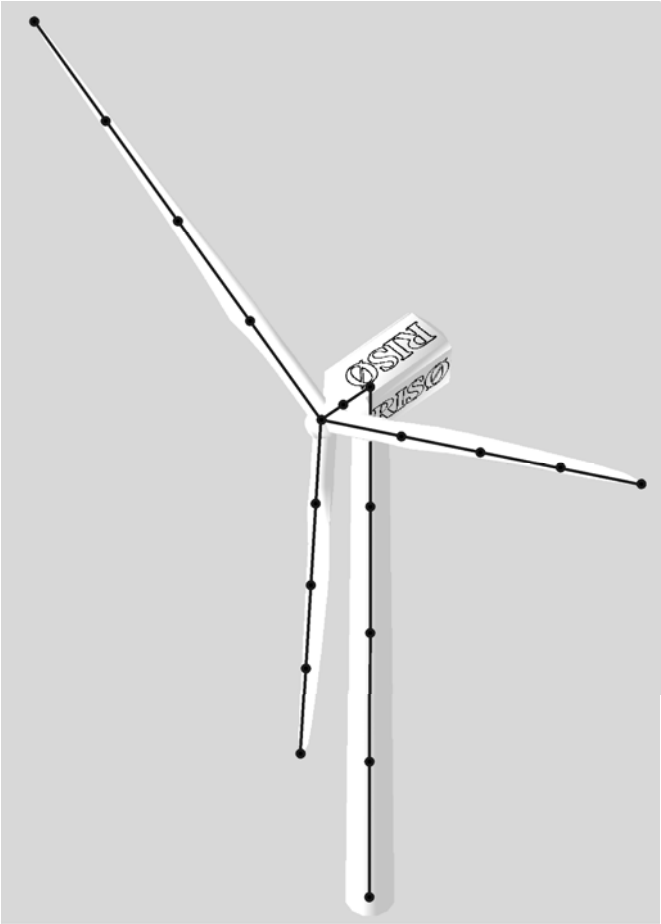


Conclusions

- A new tool for determination of dynamic and static stability as been developed and verified
- The effect of a TE control system may severely change the flutter/divergence velocity of a 2D airfoil section
- The effects are not always easy to understand
- If possible, TE control systems should shut themselves off at free-running situations if there is no gain scheduling in the flap control
- For the investigated case, AOA control is more stable than Y control



Future work...

- Get to know the tool better
- Determine typical behavior of different types of TE systems
- Determine typical behavior of some more realistic control algorithms
- Active flutter suppression and divergence suppression