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Flexible aircraft control based on an adaptive output feedback control scheme

J. Bordeneuve-Guibé

Research Team ADIS (System Interface, Dynamics and Control)
ISAE, Université de Toulouse
joel.bordeneuve@isae.fr

L. Bako
Ecole des Mines de Douai

R. Miksch
RWTH, Aachen

M. Jeanneau
Airbus France, Toulouse

Outline

- Introduction to the problem
- The adaptive scheme
- The flexible aircraft model
    - A reduced model
    - A possible control objective
- Simulation results
    - Choice of the reference model
    - Disturbance rejection
- Conclusions

Classical Aircraft Control Challenges

- The aircraft is considered as a flying rigid body
- Modelling an aircraft using a single model remains an inaccessible dream for control engineers
  - Many varying parameters (altitude, Mach number, CoG, take-off and landing configurations, sloshing phenomena…)
  - Complex models lead to complex controllers
- Flight domain is splitted (i.e. altitude – Mach number)
  - Many « local » models of small size
  - Each model is a Linear Time Invariant (LTI) model
  - One model leads to one controller
  - The overall controller switches between local controllers (gain scheduling)

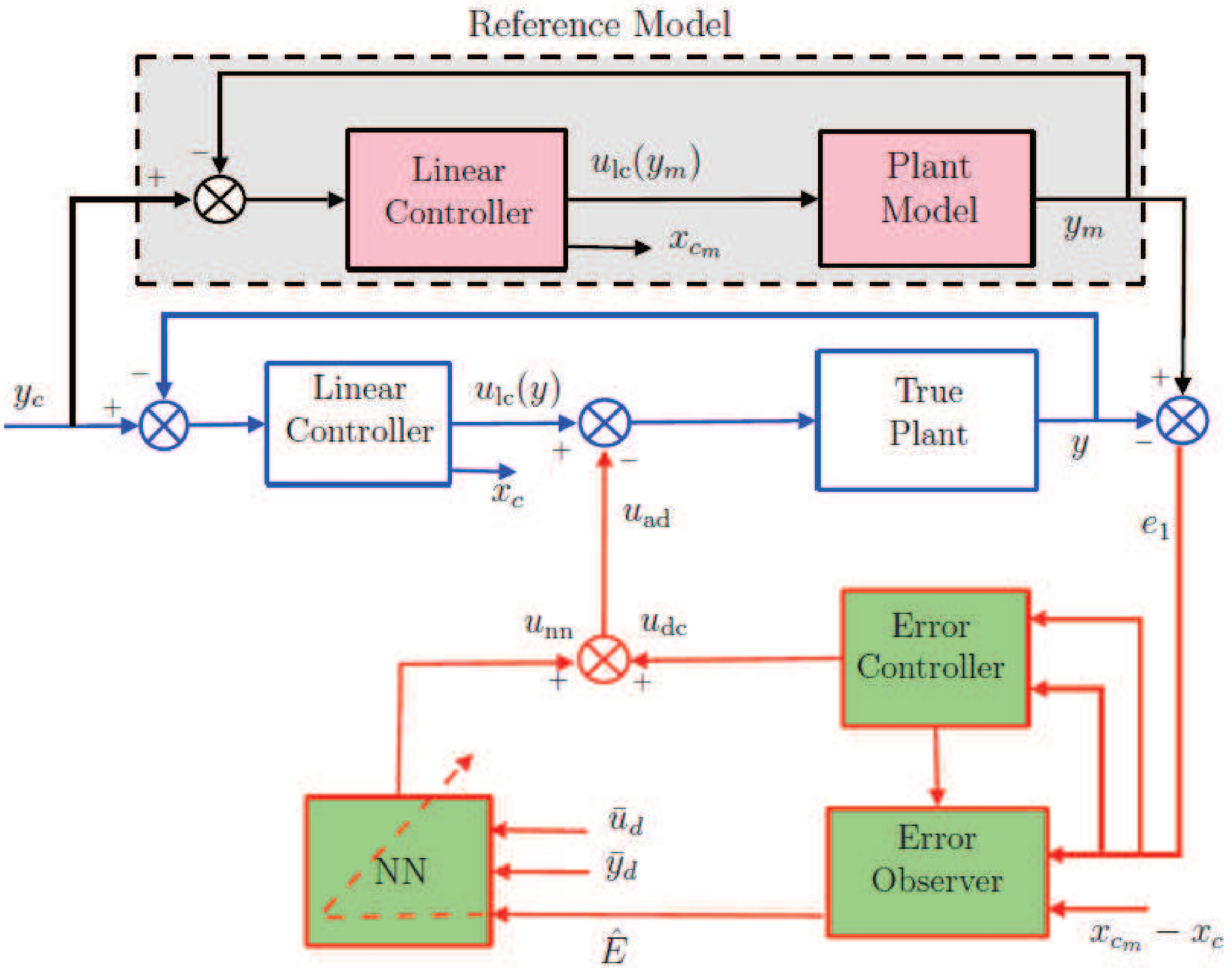
Flexible Aircraft Control Challenges

- Structural flexibility can not be ignored anymore
    - Unceasing growing size aircrafts (air traffic is still growing)
    - Increasingly light materials (more consumption constraints)
- Modelling structural flexibilities leads to partial differential equations
- But priority is still given to linear controllers
    - Control design is subject to many constraints (certification)
    - Keep the existing control structure, if possible
- One possible solution: adaptive linear control

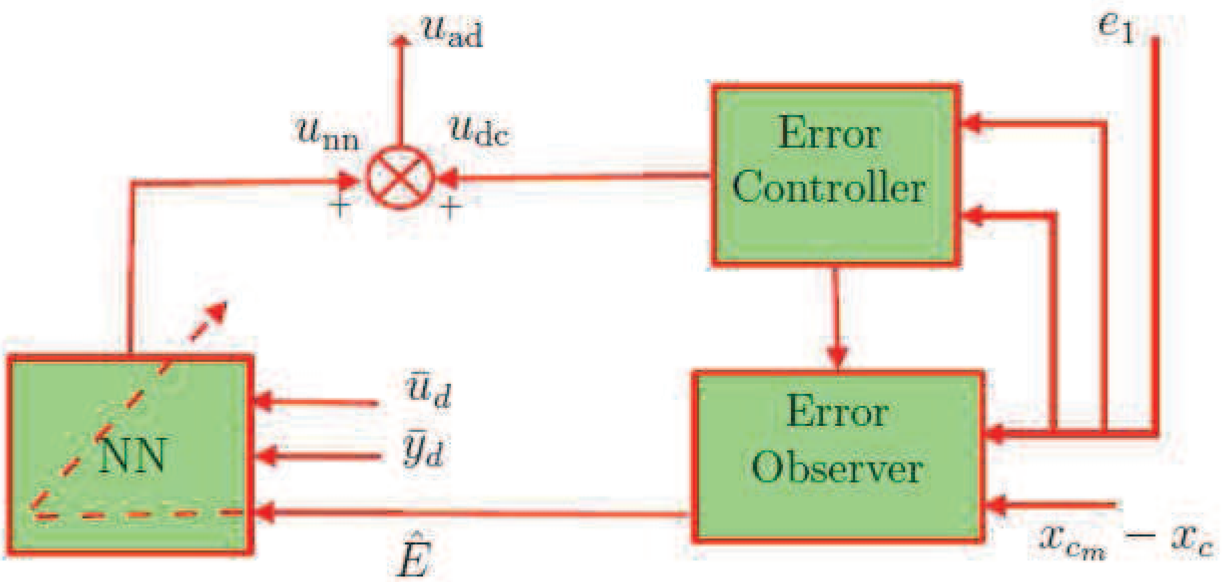
Adaptive control structure

- Key ideas:
  - Two parallel control loops (reference and adapted loops)
  - A reference model is defined on the base of the *ideal system behavior*
  - The same linear controller is applied to both reference loop and adapted loop
  - Adaptation is based on the output error signal (uncertainties, unmodelled dynamics, disturbances, etc…)
- Constraint:
  - The linear controller has to be kept linear and simple

Adaptive control structure



Adaptive control with reference model



- **Error observer**: *estimates* the states of the error dynamic $\hat{E}$ from $e_1 = y_m(t) - y(t)$ and from the controller state error $x_{cm}(t) - x_c(t)$
- **Neural Network**: *builds* the uncertain dynamic Δ from input/output data and from $\hat{E}$
- **Error controller (optional)**: *speeds up* the learning process and *improves* estimation accuracy

$$\boxed{u_{ad} = u_{nn} + u_{dc}}$$

Adaptive control with reference model

- Hypothesis: system G of order *n* is observable and controllable

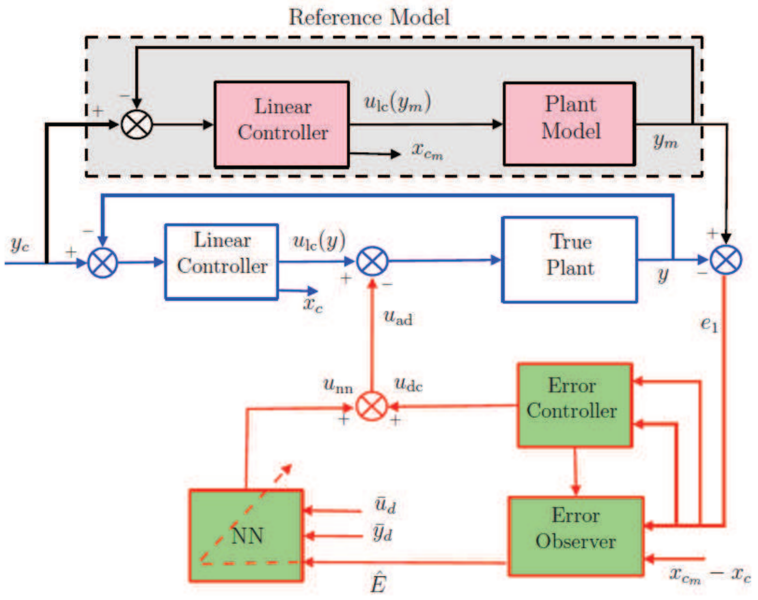
  Constraint: relative degree is known and non zero
- Reference model G_m (order *m<n)* has got the same relative degree as G

⇨ $\boxed{G = G_m + \Delta}$

1. A stabilizing controller is designed from G_m
2. This first closed loop defines a reference model
3. This controller is also applied to the system G
4. An additionnal control law (U_{ad}) is generated from the output error between both loops.

⇨ $\boxed{U = U_{LC} - U_{ad}}$

Adaptive control structure



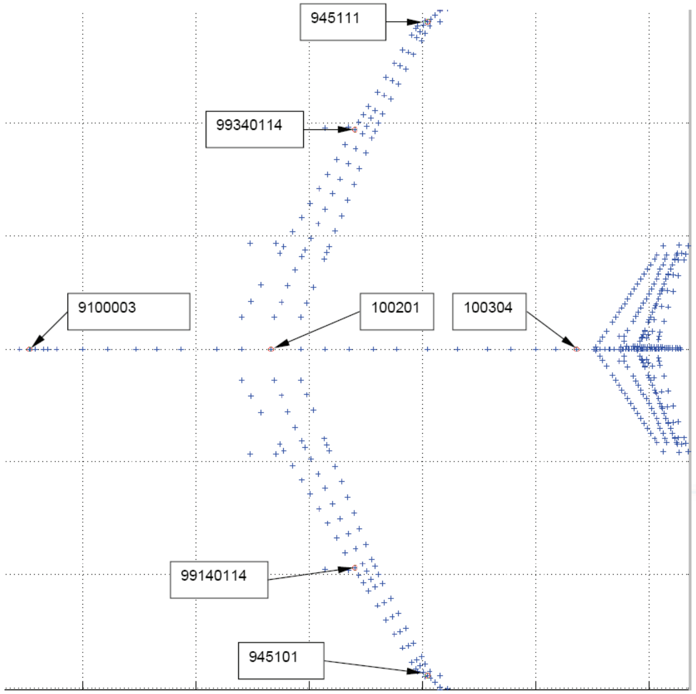
- Choice of the plant model G_m is crucial
- Structure validated experimentally for small dimension systems:

$$G = \frac{\theta_1}{u} = \frac{K_0(s^2 + 2\varsigma_{z1}\omega_{z1}s + \omega_{z1}^2)\cdot(s^2 + 2\varsigma_{z2}\omega_{z2}s + \omega_{z2}^2)}{s(s+c)\cdot(s^2 + 2\varsigma_{p1}\omega_{p1}s + \omega_{p1}^2)\cdot(s^2 + 2\varsigma_{p2}\omega_{p2}s + \omega_{p2}^2)} \quad \Rightarrow \quad G_m = \frac{K}{s(s+c)}$$

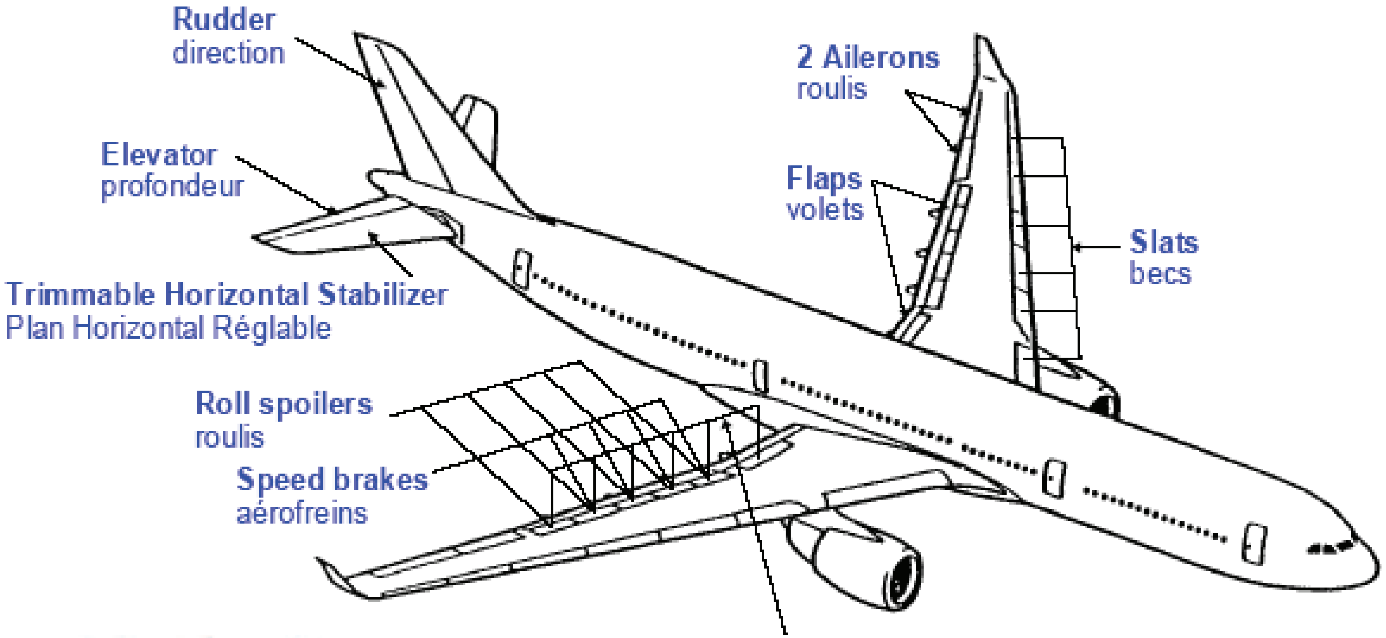
The flexible aircraft model

Only the longitudinal axis is considered (vertical plane)

- 7 inputs
  - 3 command inputs (inner and outer ailerons, elevator)
  - 1 disturbance input (wind turbulence)
- 105 outputs
  - At the CoG: Angle of attack α, pitch angle θ and rate q, vertical velocity V_z , altitude Δz and vertical acceleration n_z
  - 6 more acceleration measures (wing bending, fuselage bending/torsion, engine/wing coupling, etc.)
- 193 states
  - Actuators and sensors dynamics



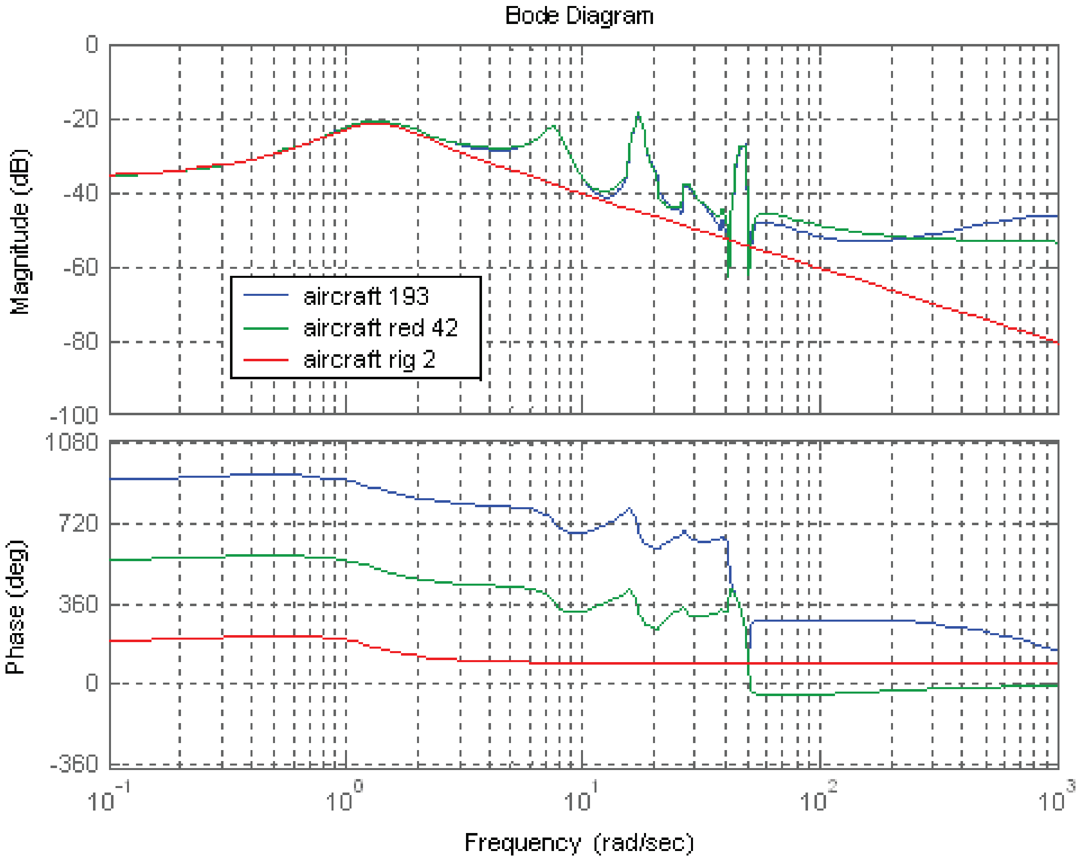
Aircraft configuration



The flexible aircraft: a reduced model

Main transfer: inner aileron --> angle of attack

- Full model (193 states)
- Reduced model (42 states)
- Rigid model (2 states)



Formulation of the control objective

- User objective:

  Reduce oscillations caused by maneuvers and/or wind gusts and shears

- Appropriate measures:

  Vertical accelerations

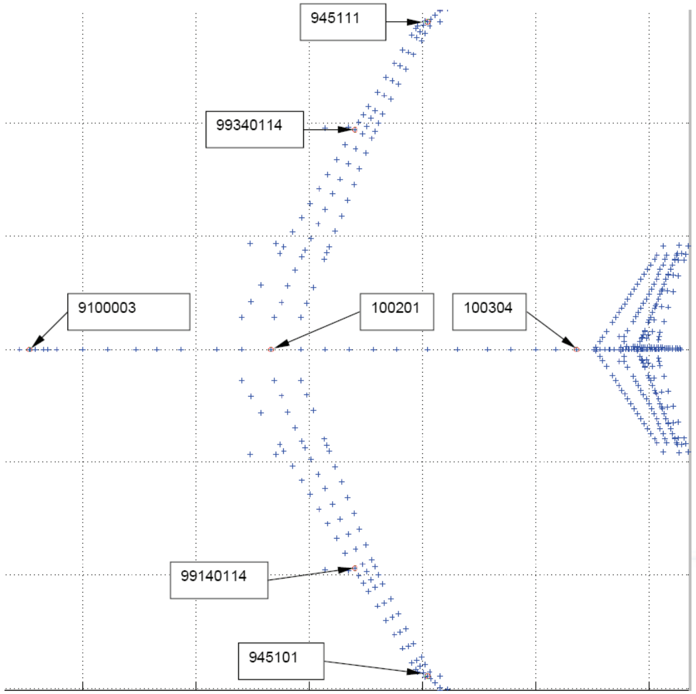
- Appropriate actuators:

  Inner ailerons

- Control objective:

  Minimize

$$\boxed{n_{zlaw} = \underbrace{\frac{n_{zR}+n_{zL}}{2}}_{\text{structure flexibility}} - \underbrace{n_{zCG}}_{\text{passengers comfort}}}$$



Adaptive control law design #1

- Reference model: rigid dynamic $(\omega_m = 1.35 rd/s \qquad \zeta = 0.4)$

  Input: inner ailerons

  Output: pitch rate *q*

$$\begin{cases} \dot{x}_m = Ax_m + Bu \\ y_m = q \end{cases} \qquad \text{with} \qquad x_m = \begin{bmatrix} \alpha \\ q \end{bmatrix}$$

- Main controller: state feedback to improve the damping ratio (around 0.7)

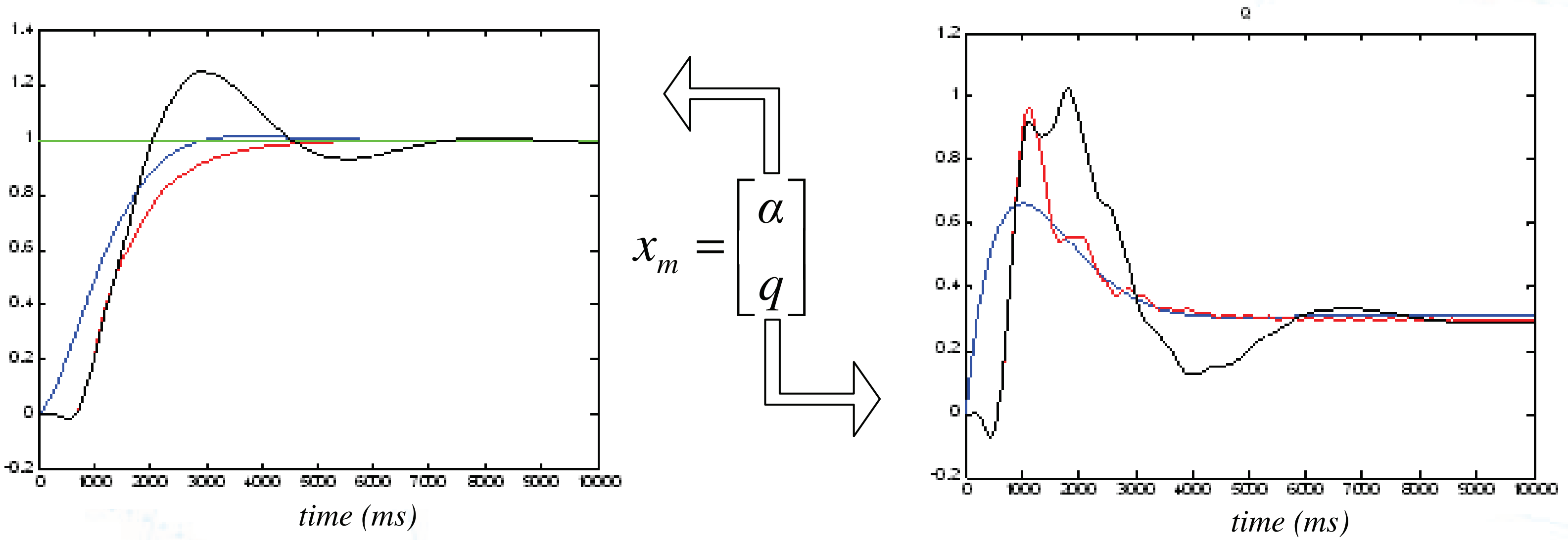
$$u_{lc} = k_c y_c - k_1\alpha - k_2 q$$

- Error controller: not used
- Error observer: not used
- Neural network

  Single hidden layer with 5 neurons

Adaptive control law design #1

- setpoint signal: step for pitch rate



$$x_m = \begin{bmatrix} \alpha \\ q \end{bmatrix}$$

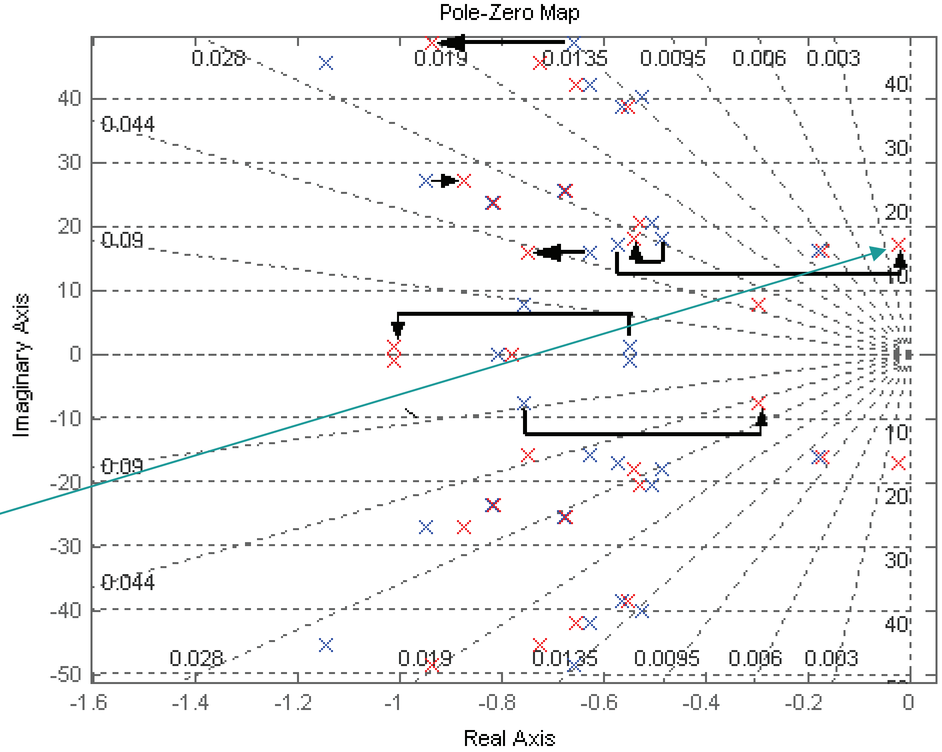
(open loop in **black**, reference model in **blue**, complete model in **red**)

- q more sensitive to the 2.7Hz mode than α
- Neural adaptation unable to improve the pitch rate behavior
  - The reference model is too restrictive
  - n_{zlaw} is not used explicitely

Adaptive control law design #1

- Pole/zero map clearly shows a migration of some flexible modes: spillover!

the 2.7Hz mode moves close to the imaginary axis!

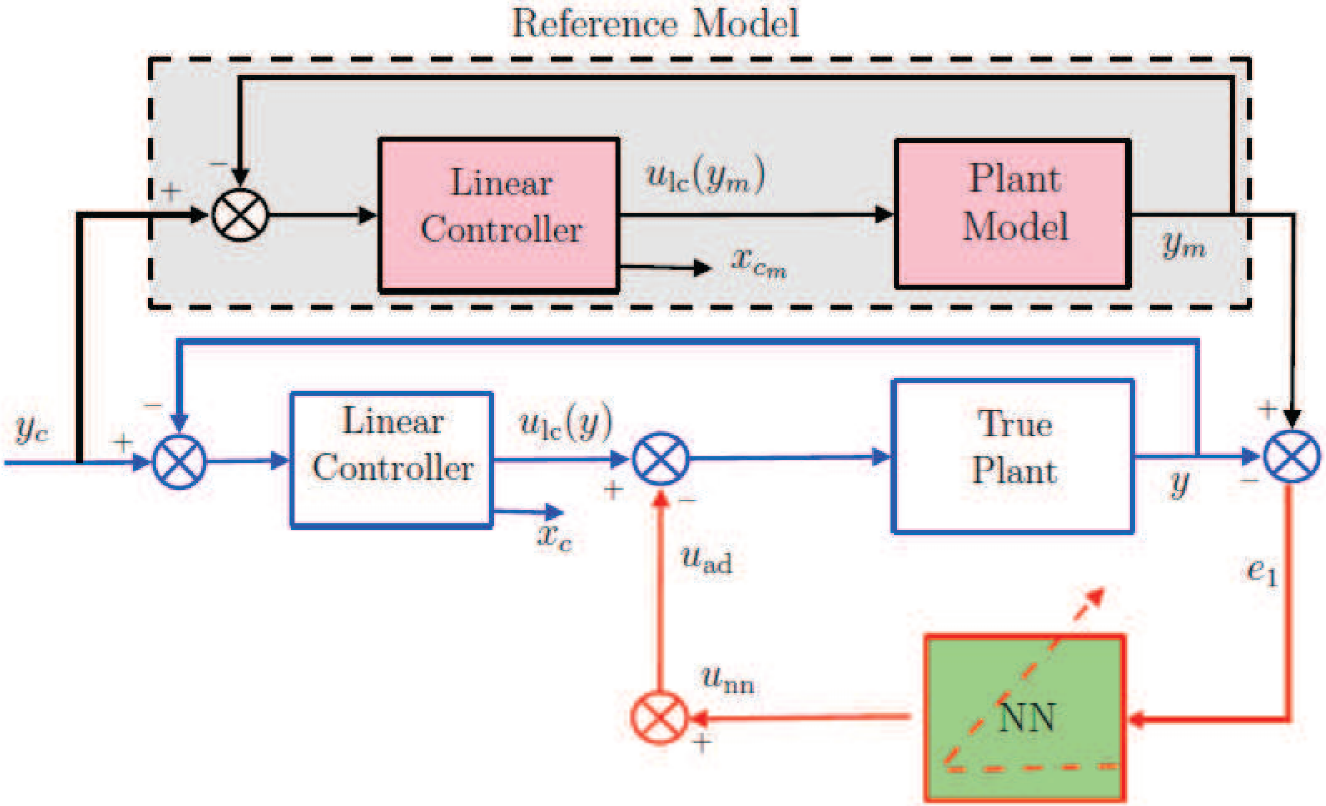


Open loop (blue crosses) and closed loop (red crosses)

Adaptive control law design #2

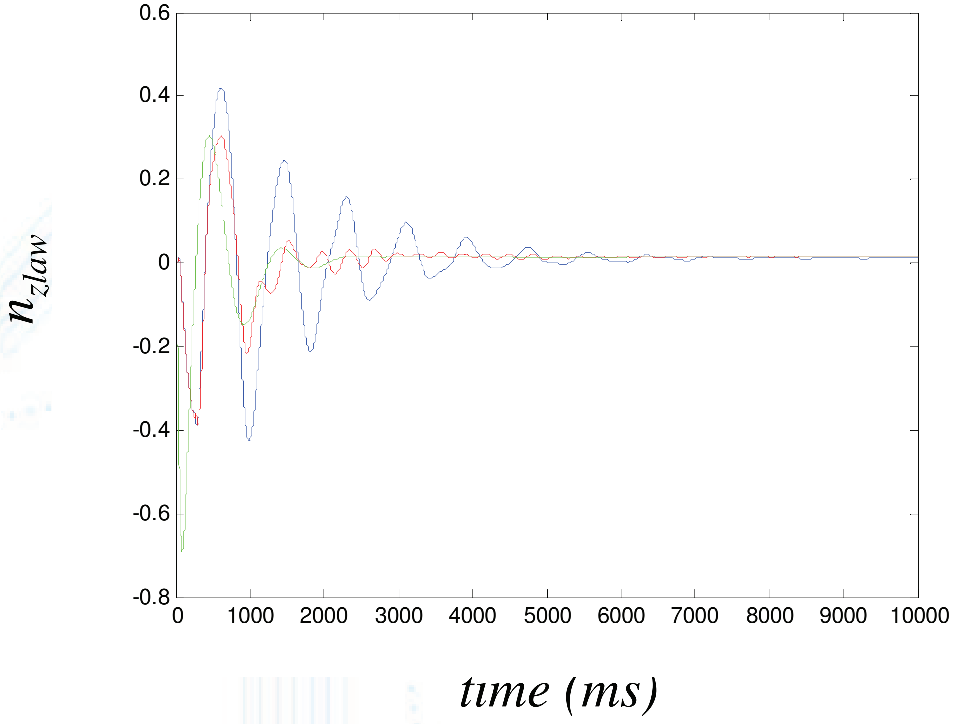
- Reference model: order 7 ⟹ $\begin{cases} \dot{x}_m = Ax_m + Bu_{lc} \\ y_m = n_{zlawref} = Cx_m \end{cases}$
  - Rigid dynamic + actuators dynamic + first flexible mode (1.2Hz)
  - Input: inner ailerons
  - Controlled output: n_{zlaw}
- Main control law:
  - LQR design $J = \int \left(x_m Q x_m + R u_{lc}^2 \right) dt$ ⟹ $u_{lc} = k_c y_c - K x_m$
- Error controller: not used
- Error observer: not used ⟹ $\hat{E} = e_1 = n_{zlawref} - n_{zlaw}$
- Neural network:
  - Single hidden layer with 7 neurons
  - Input: $e_1 = n_{zlawref} - n_{zlaw}$

Adaptive control law design #2



Adaptive control law simulation

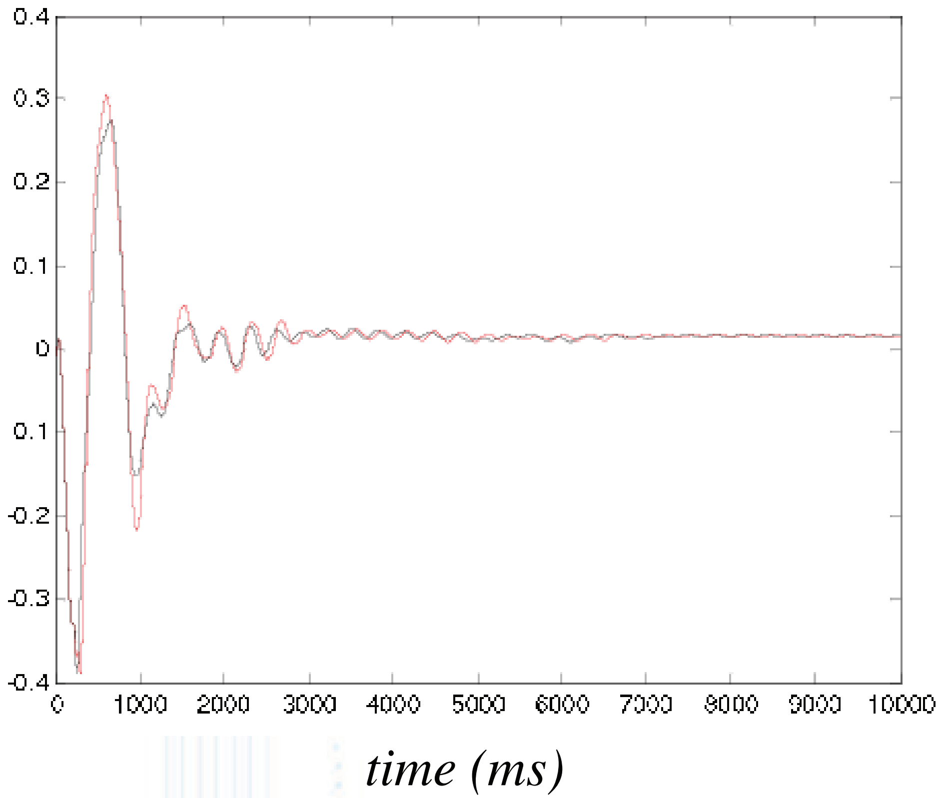
- Reference signal: step input on n_{zCG}



- Open loop (blue line)
- Reference model output $n_{zlawref}$ (green line)
- Controlled output n_{zlaw} (red line)

Adaptive control law simulation

- Effects of the adaptation on the control signal

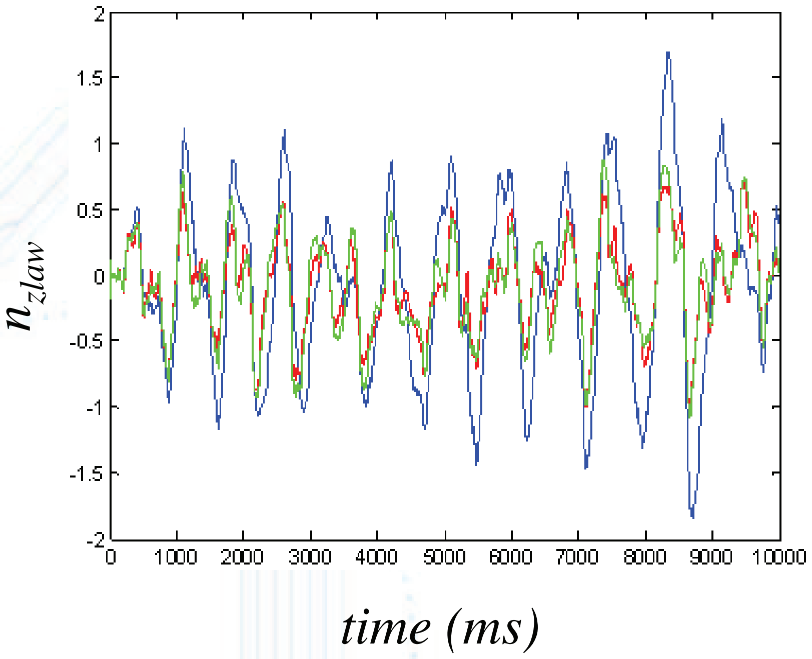


- Controller output u_{lc} (red line)
- Total control signal $u_{lc} + u_{nn}$ (black line)

Another simulation: disturbance rejection

- Setpoint is zero
- Simulation of wind gusts
- Error controller added →

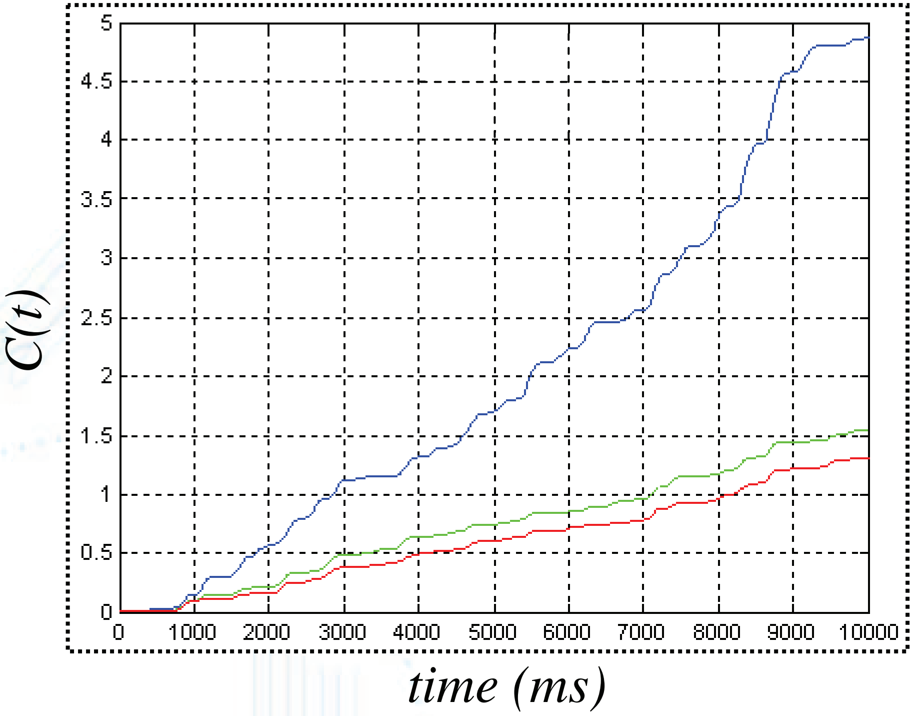
$$u_{dc} = 20\frac{s+3}{s+50}\left(n_{zlawref} - n_{zlaw}\right)$$



- Open loop (blue line)
- Reference model output $n_{zlawref}$ (green line)
- Controlled output n_{zlaw} (red line)

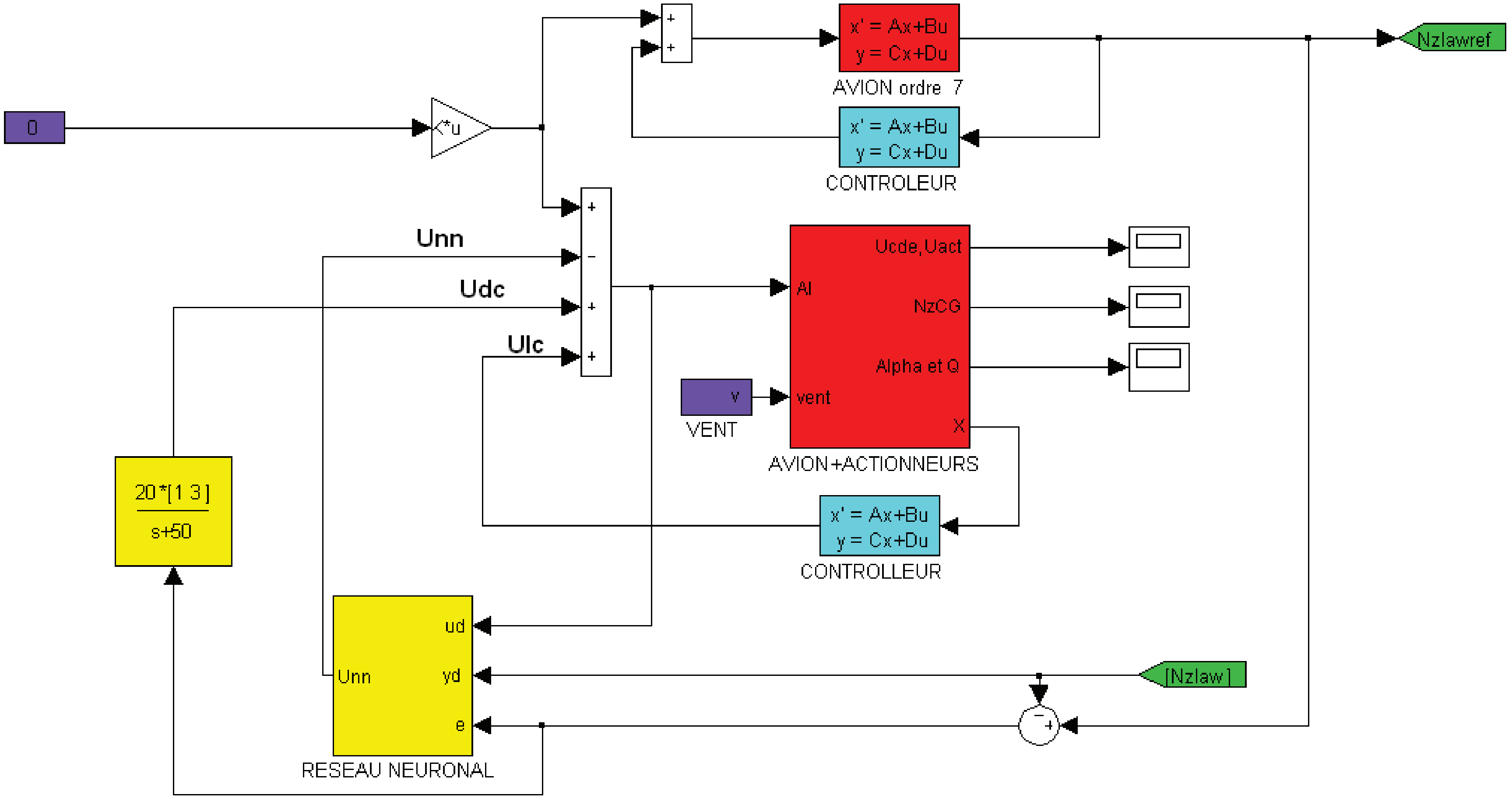
Another simulation: disturbance rejection

- An appropriate performance index ? ⟹ $C(t) = \int_0^t n_{zlaw}^2(t)dt$



- In open loop (blue line)
- Without adaptation (green line)
- With adaptation (red line)

Full Matlab Simulink simulation



Conclusions and future work

- The basic idea of adaptive control based on a closed loop reference model seems adapted for high dimension systems
- The use of neural networks is not crucial (it can be replaced by conventional methods)
- Closed loop performances are still difficult to evaluate

- Real-time application on the « liquid sloshing » set-up