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Flexible aircraft control based on an adaptive output feedback control scheme

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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 $\Delta$ from input/output data and from $\hat{E}$
- **Error controller (optional)**: speeds up the learning process and improves estimation accuracy

$$u_{ad} = u_{nn} + u_{dc}$$
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 $G$

  $$G = G_m + \Delta$$

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 additional control law ($u_{ad}$) is generated from the output error between both loops.

  $$U = U_{LC} - U_{ad}$$
Adaptive control structure

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

\[
G = \frac{\theta_1}{u} = \frac{K_0(s^2 + 2\zeta_{z1}\omega_{z1}s + \omega_{z1}^2) \cdot (s^2 + 2\zeta_{z2}\omega_{z2}s + \omega_{z2}^2)}{s(s + c) \cdot (s^2 + 2\zeta_{p1}\omega_{p1}s + \omega_{p1}^2) \cdot (s^2 + 2\zeta_{p2}\omega_{p2}s + \omega_{p2}^2)}
\]

\[
G_m = \frac{K}{s(s + c)}
\]
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 $\alpha$, pitch angle $\theta$ and rate $q$, vertical velocity $V_z$, altitude $\Delta z$ 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
  \[ n_{z_{law}} = \frac{n_{zR} + n_{zL}}{2} - n_{zCG} \]

  structure flexibility  passengers comfort
Adaptive control law design #1

- **Reference model**: rigid dynamic \((\omega_m = 1.35 \text{rad/s} \quad \zeta = 0.4)\)
  - Input: inner ailerons
  - Output: pitch rate \(q\)

\[
\begin{align*}
\dot{x}_m &= Ax_m + Bu \\
y_m &= q
\end{align*}
\]

with \(x_m = \begin{bmatrix} \alpha \\ q \end{bmatrix}\)

- **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 \( \alpha \)
- Neural adaptation unable to improve the pitch rate behavior
  - The reference model is too restrictive
  - \( n_{z\text{low}} \) is not used explicitly
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
  Rigid dynamic + actuators dynamic + first flexible mode (1.2Hz)
  Input: inner ailerons
  Controlled output: \( n_{zlaw} \)

• Main control law:
  LQR design
  \[ J = \int (x_m Q x_m + R u_{lc}^2) dt \]
  \[ u_{lc} = k_c y_c - K x_m \]

• 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?

\[ C(t) = \int_0^t n_{z\text{law}}^2(t) dt \]

- 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