ADAPTIVE PASSIFICATION-BASED FAULT-TOLERANT FLIGHT CONTROL

A.L. Fradkov[1], B. Andrievsky[1], D. Peaucelle[2]

[1]CCS Lab., Institute for Problems of Mechanical Engineering of RAS, St.Petersburg

http://www.ipme.ru/ipme/lab`s/ccs

[2]Laboratoire d'analyse et d'architecture des systèmes, LAAS-CNRS, Toulouse
http://www.laas.fr/~peaucell/

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Abstracts

The adaptive passification-based method is used for fault-tolerant flight control design.

Simulation results for HL-20 model and results of experiments with the "LAAS Helicopter Benchmark" are presented, showing efficiency and fault-tolerance of the proposed method.

OUTLINE

1. **Introduction**
2. **Passification method and adaptive controllers with Implicit Reference Model**
3. **Adaptive fault-tolerant control for HL-20**
   - *3.1 IRM adaptive controller for HL-20 angle of attack*
   - *3.2 Simulation results*
4. **Adaptive fault-tolerant control for LAAS Helicopter benchmark**
   - *4.1 IRM adaptive controller for the 'Helicopter' pitch angle*
   - *4.2 Experimental results*

Conclusions

2. Passification method and adaptive controllers with Implicit Reference Model

LTI SISO system

$$A(p)y(t) = B(p)u(t), \quad t \geq 0, \qquad (1)$$

u **- scalar control signal,** ***y*** **– controlled output;**

$$A(p) = p^n + a_{n-1}p^{n-1} + \cdots + a_0$$

$$B(p) = b_m p^m + b_{m-1}p^{m-1} + \cdots + b_0$$

-uncertain polynomials on ***p=d/dt*****.**

Plant model parameters are unknown.

<u>Control problem</u>:

tracking the reference (command) signal $y_{\mathrm{ref}}(t)$**.**

Implicit Reference Model (IRM)

Introduce $\sigma(t)=G(p)y(t)-D(p)\,y_{\mathrm{ref}}(t)$ - the *adaptation error* signal,

$$G(p)=p^{l}+g_{l-1}p^{l-1}+\cdots+g_{0},\ D(p)=d_{s}p^{s}+d_{s-1}p^{s-1}+\cdots+d_{0}$$

-given polynomials, specifying desired properties of the closed-loop system; $G(\lambda)$ - stable (Hurwitz) polynomial.

The signal $\sigma(t)$ – *the equation error* for the equation

$$G(p)y_{*}(t)=D(p)y_{\mathrm{ref}}(t), \qquad (2)$$

$\sigma(t)\equiv 0 \Longrightarrow$ **controlled variable $y(t)$ satisfies (2).**

Hence (2) represents reference model implicitly; it is called the *Implicit Reference Model* (IRM).

Adjustable control law

Adjustable control law in the *main loop*:

$$u(t) = k_r(t)\Big(D(p)y_{ref}(t)\Big) + \sum_{i=0}^{l} k_i(t)(p^i y(t)), \quad (3)$$

$\boldsymbol{k_r(t)}$, $\boldsymbol{k_i(t)}$, $(\boldsymbol{i = 0,1,\ldots,l})$ **- tunable parameters**

Adaptation algorithm

The passification based design method leads to the following *adaptation algorithm*:

$$\dot{k}_r(t) = \gamma\sigma(t)D(p)y_{\text{ref}}(t) - \alpha(k_r(t) - k_r^0), \quad k_r(0) = k_r^0, \quad (4a)$$

$$\dot{k}_i(t) = -\gamma\sigma(t)p^i y(t) - \alpha(k_i(t) - k_i^0), \quad k_i(0) = k_i^0, \quad (4b)$$

$\gamma > 0$ - *adaptation gain*;

$\alpha \geq 0$ - *parametric feedback gain*;

k_r^0, k_i^0 - prior estimates of the appropriate values of the tunable parameters, $i = 0, 1, \ldots, l$.

Applicability conditions – Passification Theorem

The adaptive controller (3), (4) applicability conditions (Passification Theorem; *Fradkov, 1974*):

1. $B(\lambda)$ **is Hurwitz polynomial,**
2. $l = k-1$; **where** $k = n-m$ **- plant (1)** ***relative degree.***

The degree of $D(p)$ is bounded by the amount of available derivatives of $y_{\mathrm{ref}}(t)$ and is subjected to designer's decision. A *matching condition* (used for the Model Reference Systems) is not necessary for IRM adaptive controllers. The order of reference equation (2) is equal to l and can be significantly less then the plant model order n.

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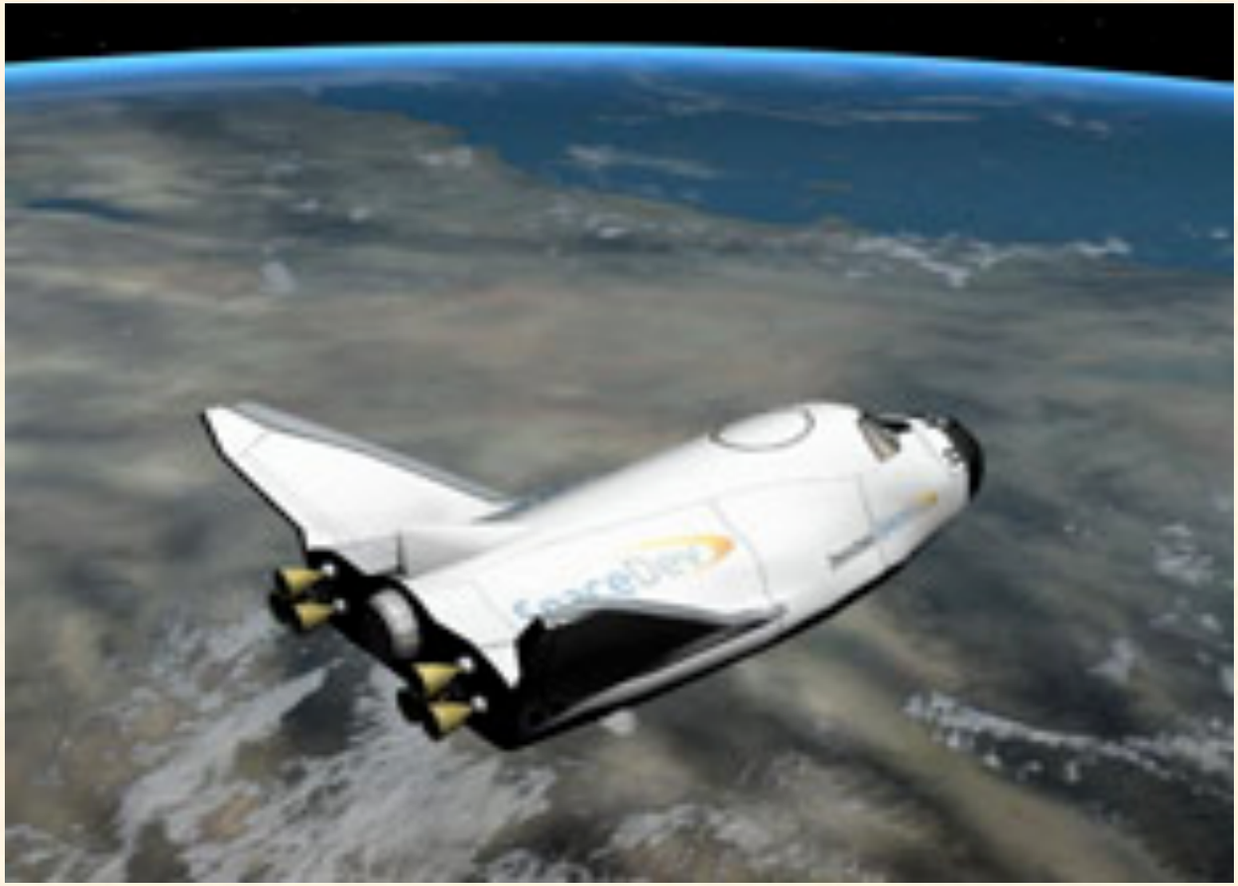
3. Adaptive fault-tolerant control for HL-20 spacecraft



[**Matlab/Simulink Aerospace Blockset demo** aeroblk_HL20.mdl]

IRM adaptive controller for HL-20 angle of attack

$$u(t) = k_I(t)\int_0^t e(t)\,\mathrm{d}\,t + k_\alpha(t)e(t) - k_q(t)q(t)$$

α – angle of attack, q –pitch rate, $e = \alpha_{\mathrm{ref}} - \alpha$ - reference error

$$\begin{cases} \dot{k}_I = -\gamma_I\sigma_t\int_0^t e(t)\,\mathrm{d}\,t + \lambda(k_I^0 - k_I(t), \\ \dot{k}_\alpha = -\gamma_\alpha\sigma_t e(t) + \lambda(k_\alpha^0 - k_\alpha(t)), \\ \dot{k}_q = \gamma_q\sigma_t q(t) + \lambda(k_q^0 - k_q(t)), \end{cases}$$

$$\sigma_t = g_I\int_0^t e(t)\,\mathrm{d}\,t + e(t) - g_q q(t)$$

Simulation results for HL-20 flight control (nominal case)

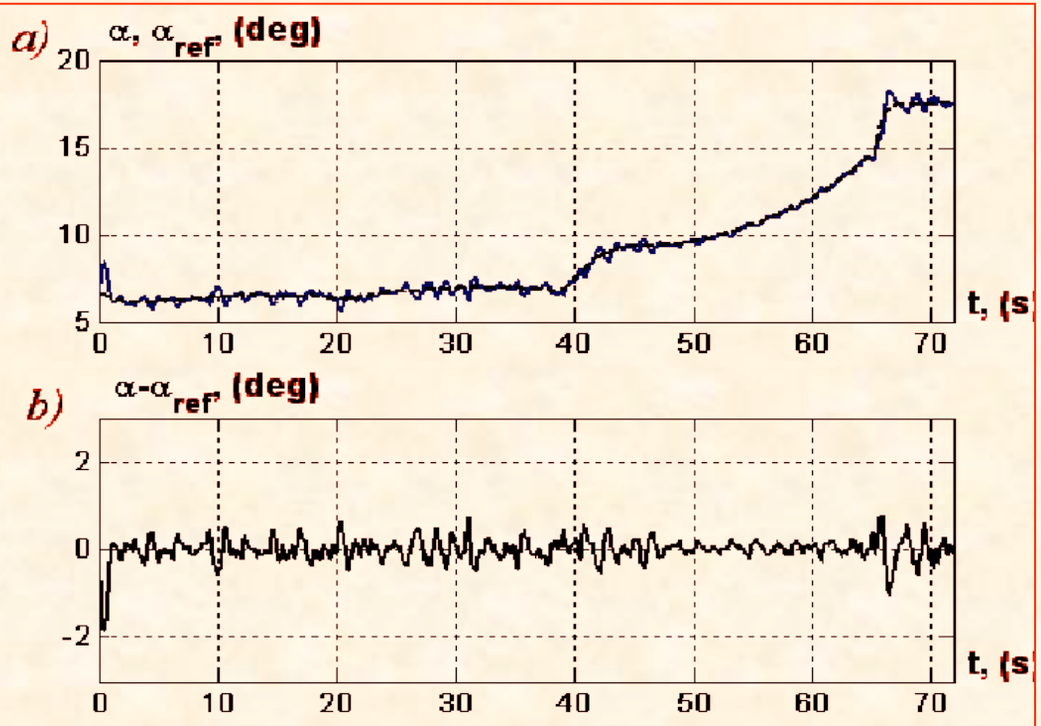


Fig. 1. Tracking the reference signal. H_∞ controller (2-D scheduling). Nominal case.

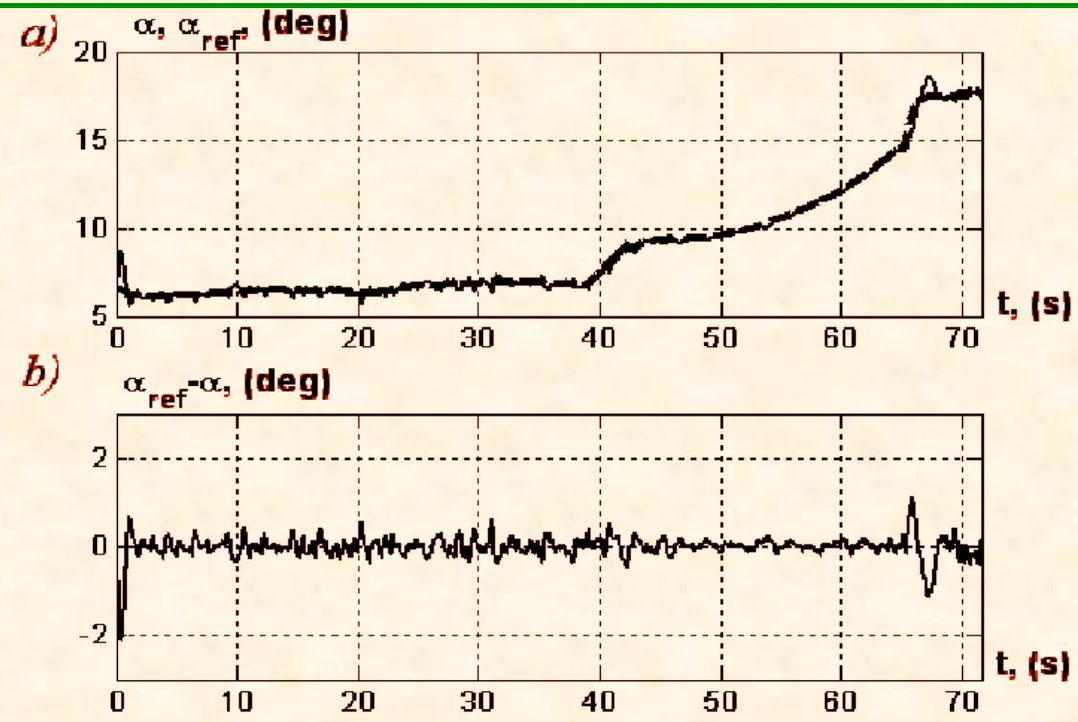


Fig. 2. Tracking the reference signal. Adaptive controller. Nominal case.

Simulation results for HL-20 (actuator fault to 45%)

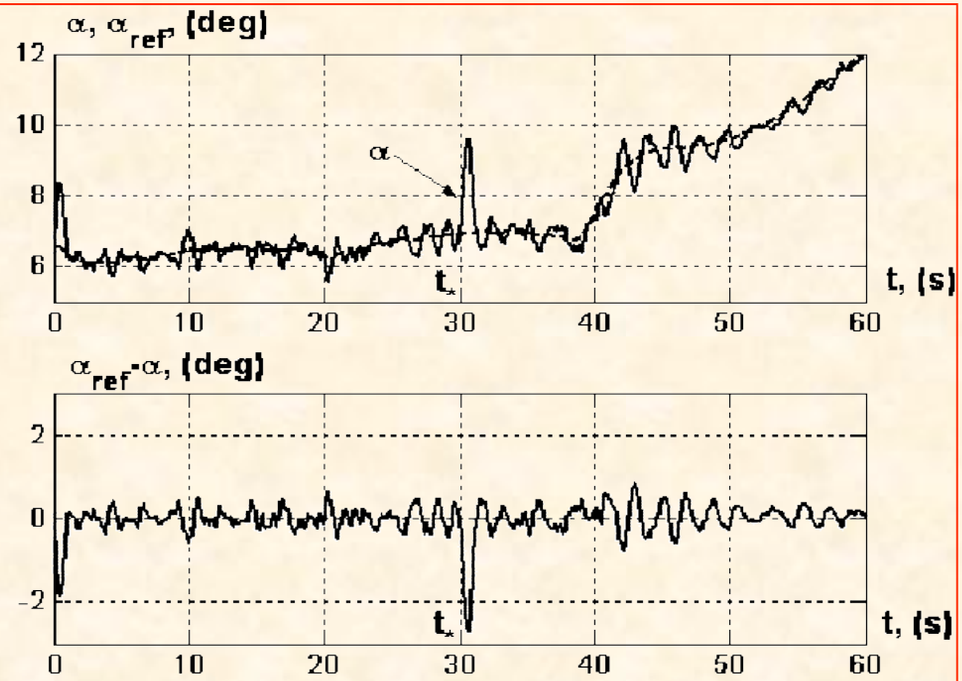


Fig. 4. Tracking the reference signal. H_∞ controller (2-D scheduling).

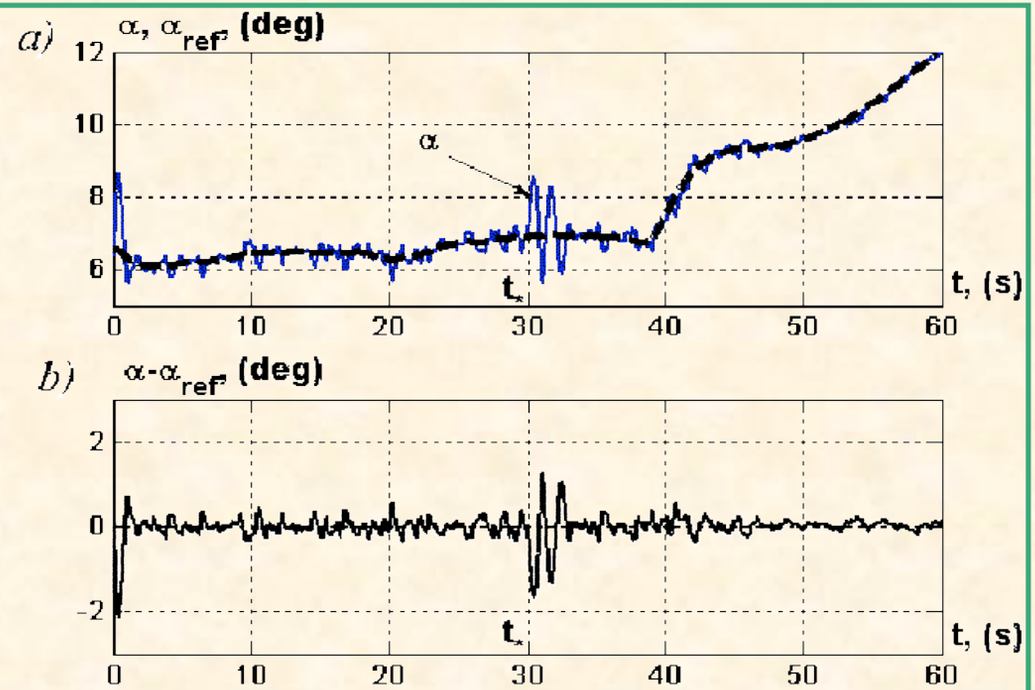
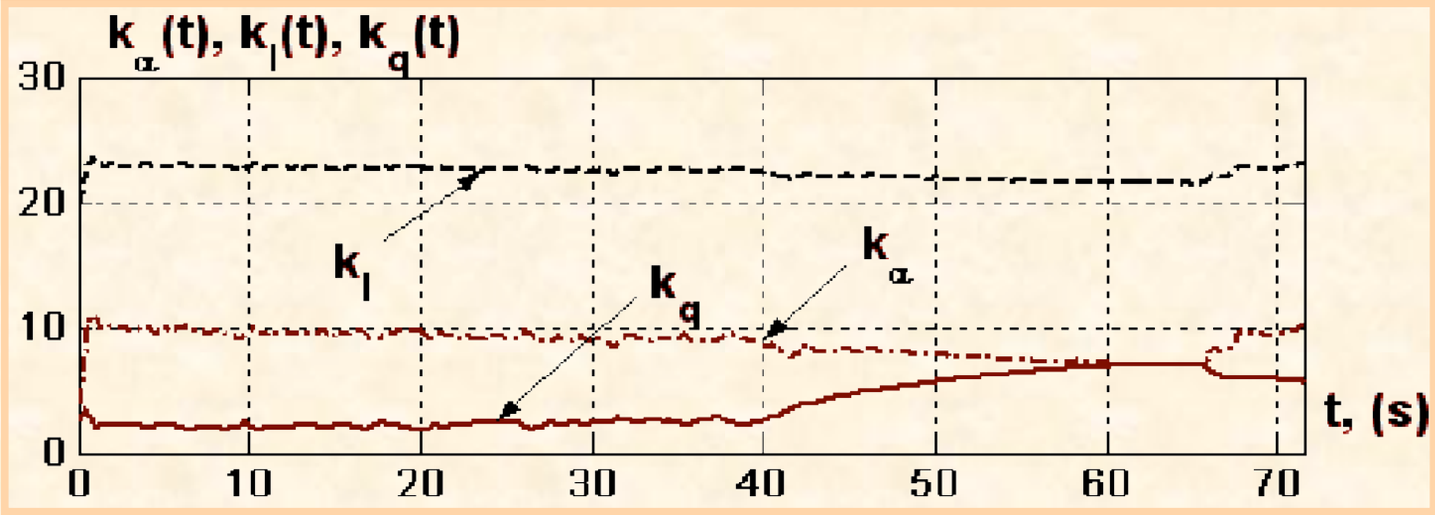
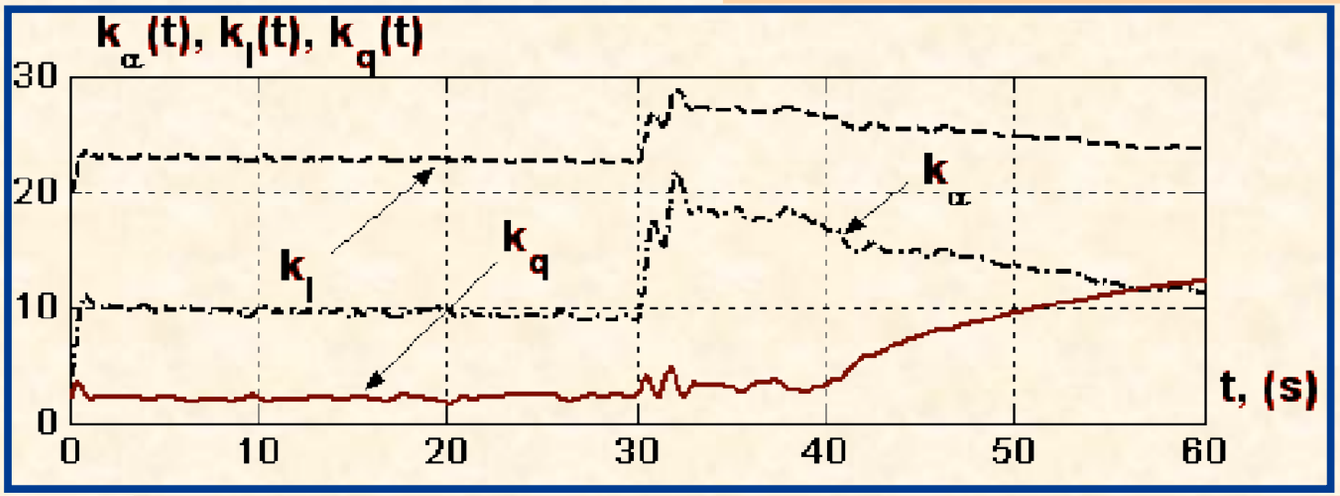


Fig. 5. Tracking the reference signal. Adaptive controller.

Simulation results for HL-20. Controller gains time histories

Nominal case





Actuator effectiveness falls down to 45% from the nominal at $t_* = 30$ s

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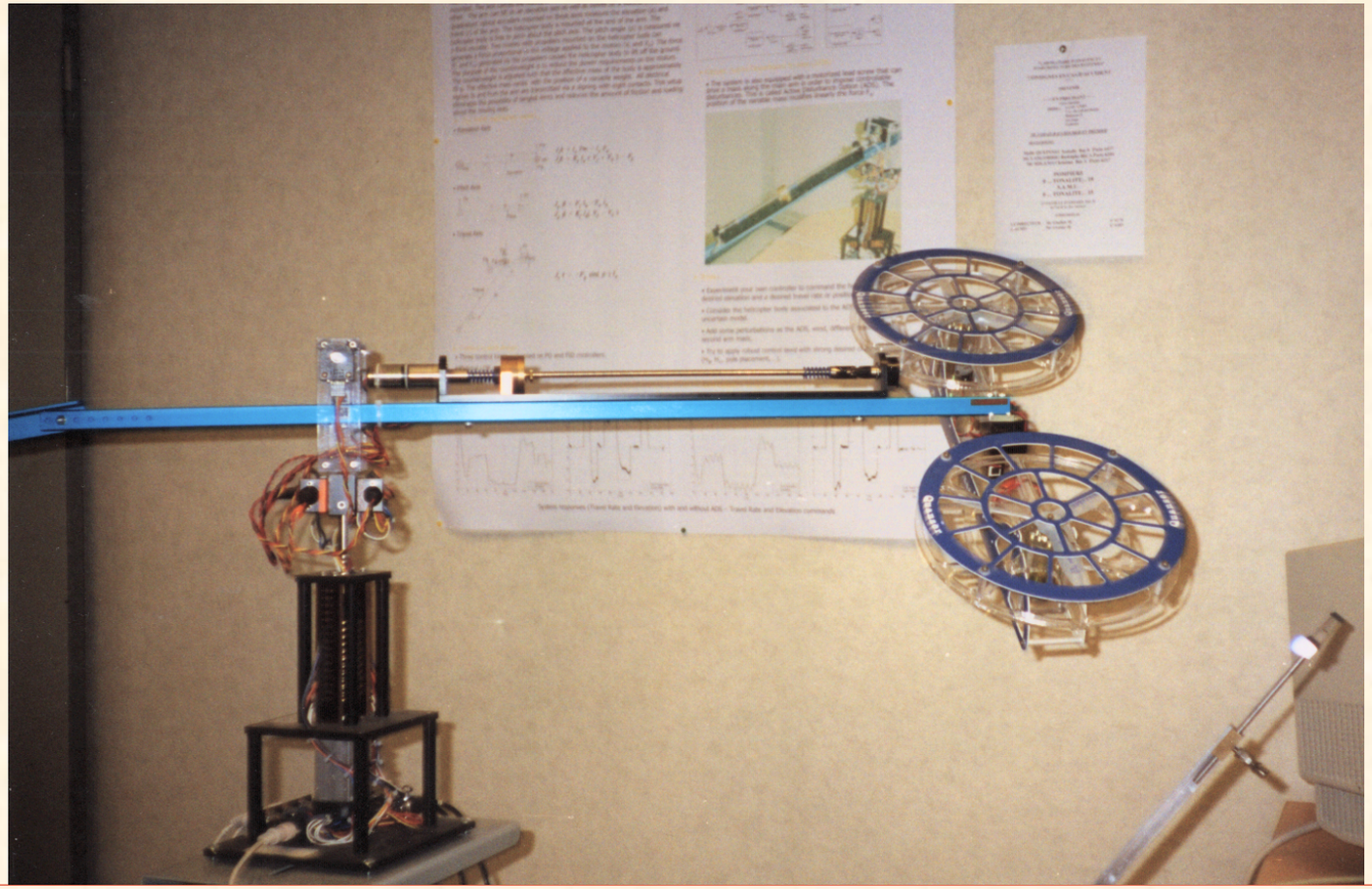
4. Adaptive fault-tolerant control for LAAS Helicopter benchmark

Quanser/LAAS "Helicopter" benchmark



Nomenclature

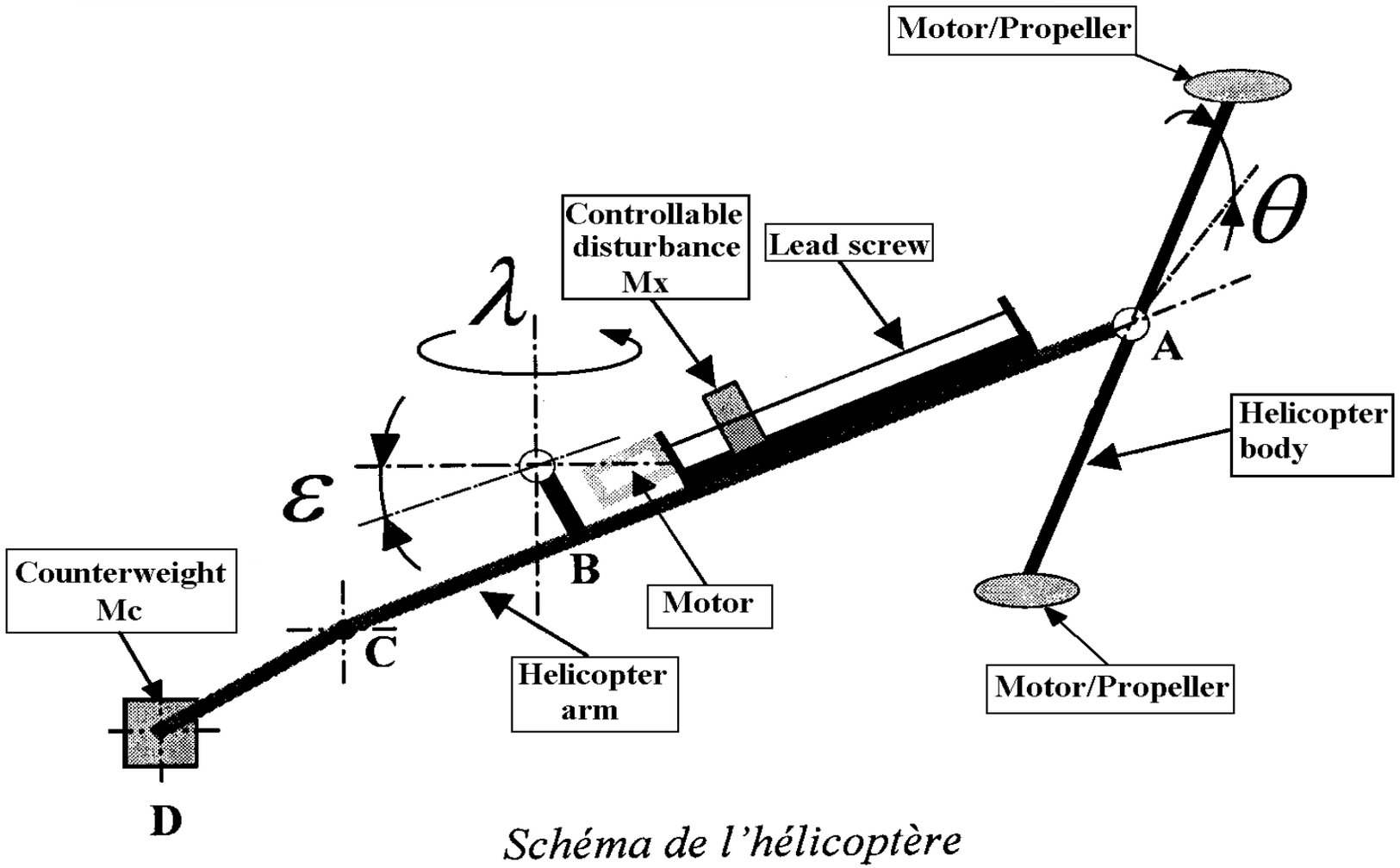


Schéma de l'hélicoptère

angles of :

θ – pitch,

λ – travel,

ε – elevation.

u_f, u_b – motor voltages;

v_x, v_z – control signals;

$u_f = 0.5(v_z + v_x)$,

$u_b = 0.5(v_z - v_x)$.

IRM adaptive PID-controller for 'Helicopter' pitch angle

$$u(t) = k_P(t)\bar{e} + k_I(t)\int_0^t \bar{e}(\tau)\,\mathrm{d}\,\tau - k_D(t)\dot{\theta}(t)$$

$$e(t) = \theta^*(t) - \theta(t), \qquad \bar{e}(t) = \mathrm{sat}_E\left(e(t)\right),\ \mathrm{sat}_E(\cdot) \in [-E, E]$$

$$\dot{k}_P(t) = -\gamma_P \sigma_t \bar{e}(t) - \alpha_P\left(k_P(t) - k_P^0\right),$$

$$\dot{k}_I(t) = -\gamma_I \sigma_t \int_0^t \bar{e}(\tau)\,\mathrm{d}\,\tau - \alpha_I\left(k_I(t) - k_I^0\right)$$

$$\dot{k}_D(t) = \gamma_D \sigma_t \dot{\theta}(t) - \alpha_D\left(k_D(t) - k_D^0\right),$$

$$\sigma_t = T\dot{\theta}(t) - \bar{e}(t)$$

Experimental results

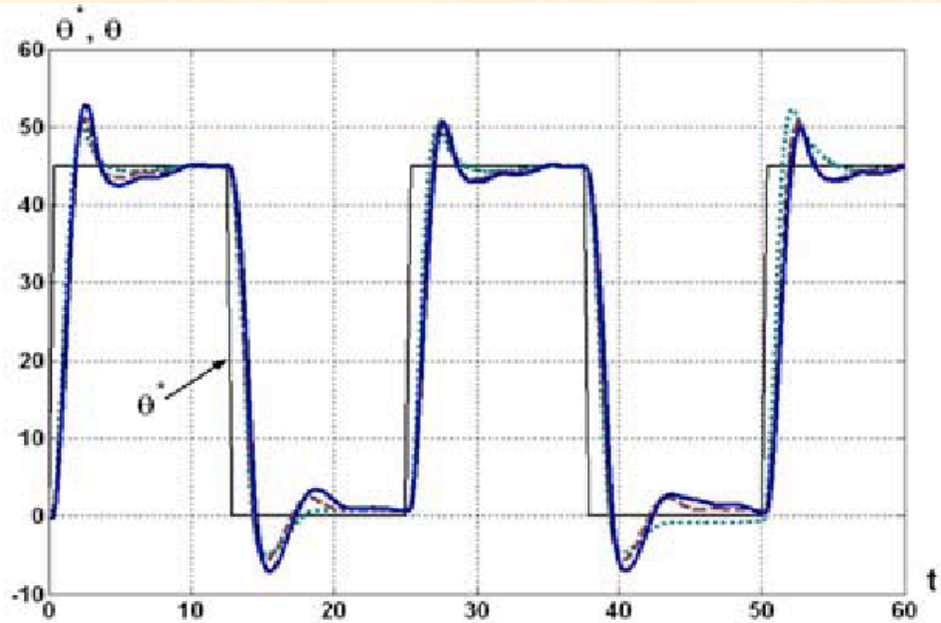


Fig. 8. Step responses of the pitch angle for system with the APID-IRM controller. Nominal case – solid line, 50% motor fault – dashed line, 100% motor fault – dotted line.

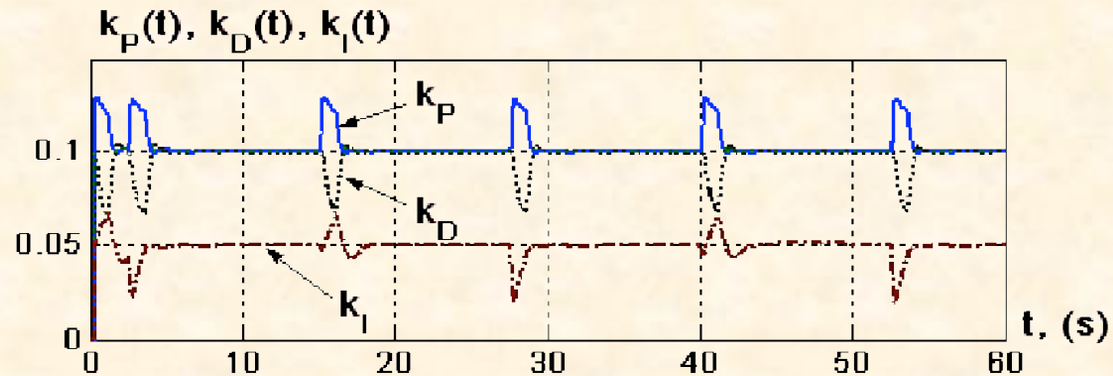
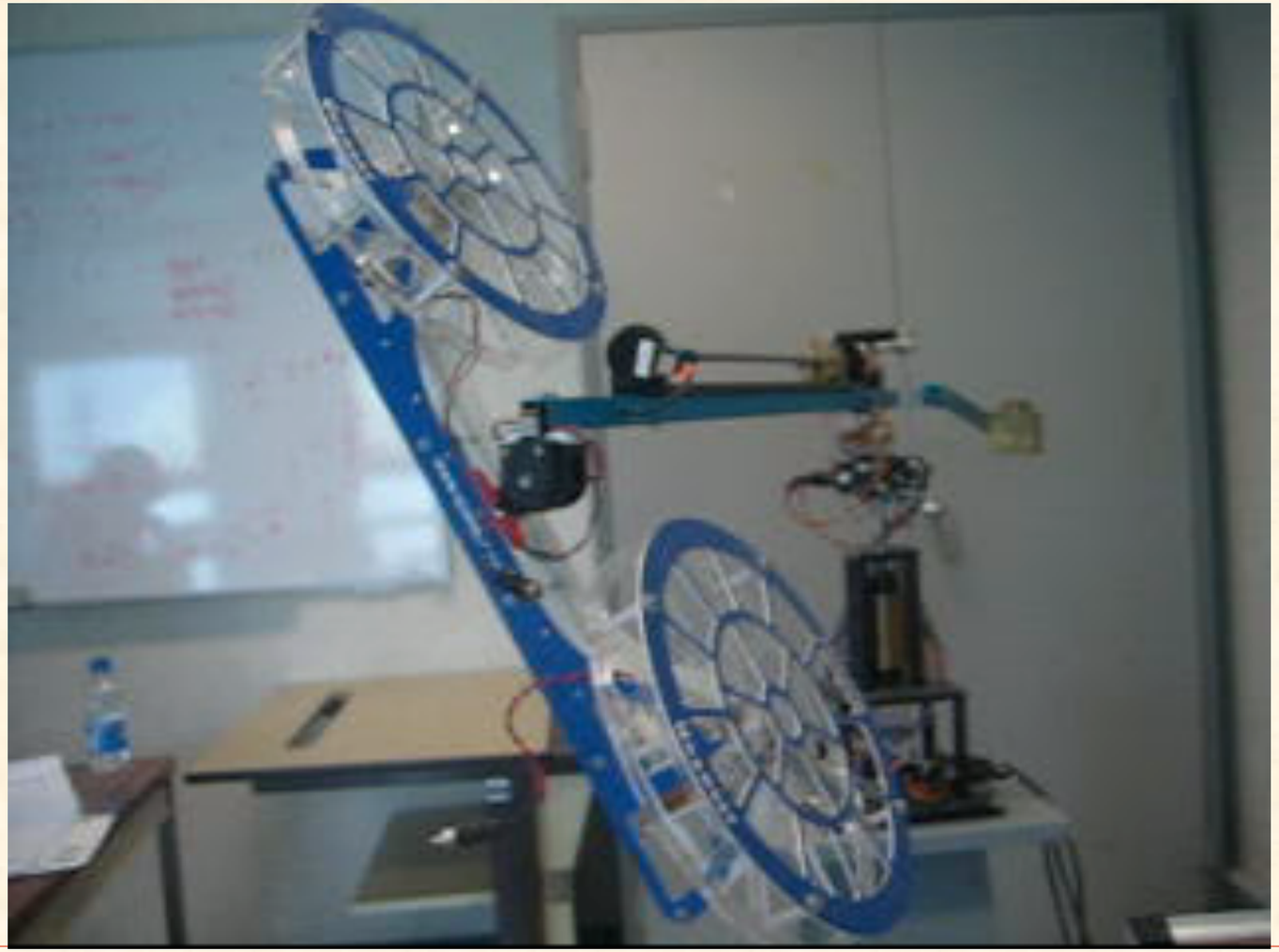


Fig. 9. Controller gains time histories; 50% motor fault.

Movie. Rear motor 100% fault



CONCLUSIONS

The adaptive passification-based method is used for fault-tolerant flight control design.
An important advantage of the proposed adaptive control is simplicity of the design procedure compared to conventional model based design.
Results of simulation for HL-20 model and experiments with the "LAAS Helicopter Benchmark" are presented, showing efficiency of the proposed method. It is demonstrated that the passification-based adaptive control approach leads to the rapid adaptive tuning algorithms, which makes it possible to use this method for actuator faults compensation.

Thank you!