# Del Control Robusto al Control Adaptable

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# From Robust Control to Adaptive Control

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## Robust Control

structured *(parameter variations)*

uncertainties

unstructured *(often in high frequencies)*

*Performance may be limited* (for large plant uncertainties)

## Adaptive Control

-Well suited for handling parameter variations
- Should work correctly in the presence of « unstructured uncertainties » (parasitics)
- Problems for large and abrupt changes in plant parameters

**Robust Control plays an important role in Adaptive Control**
(directly or indirectly)

**Adaptive Control can improve the performances of a Robust Controller**

**Identification in Closed Loop allows to establish links between Robust Control and Adaptive Control**

# Outline

- Introduction
- Identification in closed loop
- *Experimental results (flexible transmission)*
- Adaptive control strategies
- Robust control design for adaptive control
- Parameter estimators
- Adaptive control with multiple models
- *Experimental results (flexible transmission)*
- Adaptive rejection of unknown disturbances
- *Experimental results (active suspension)*
- Concluding remarks

# Plant Identification in Closed Loop

***Why ?***

There are systems where open loop operation is not suitable ( instability, drift, .. )

A controller may already exist ( ex . : PID )

Re-tuning of the controller

a) to improve achieved performances
b) controller maintenance

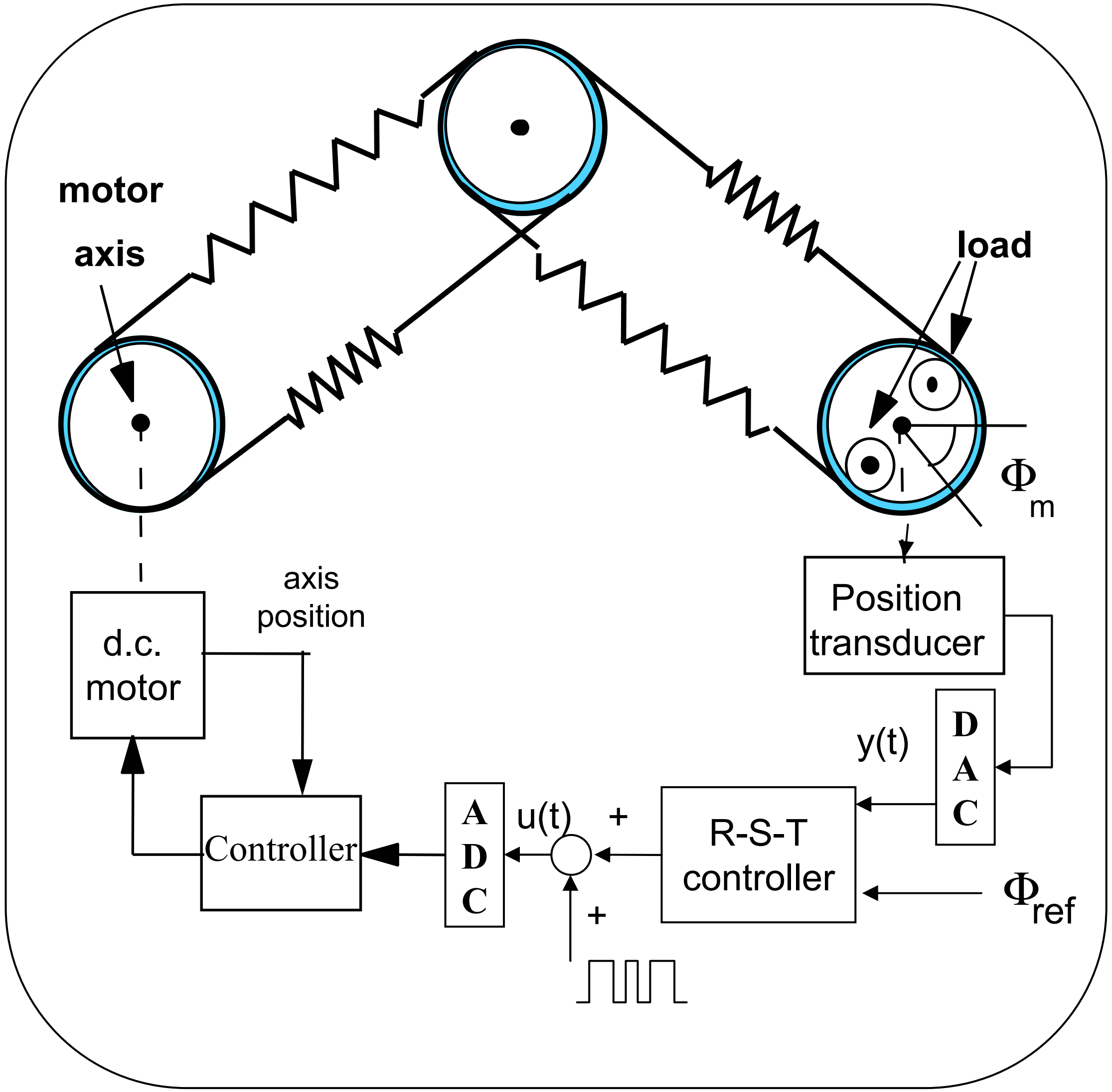
***May provide better « design » models ! !***

Iterative identification and controller redesign

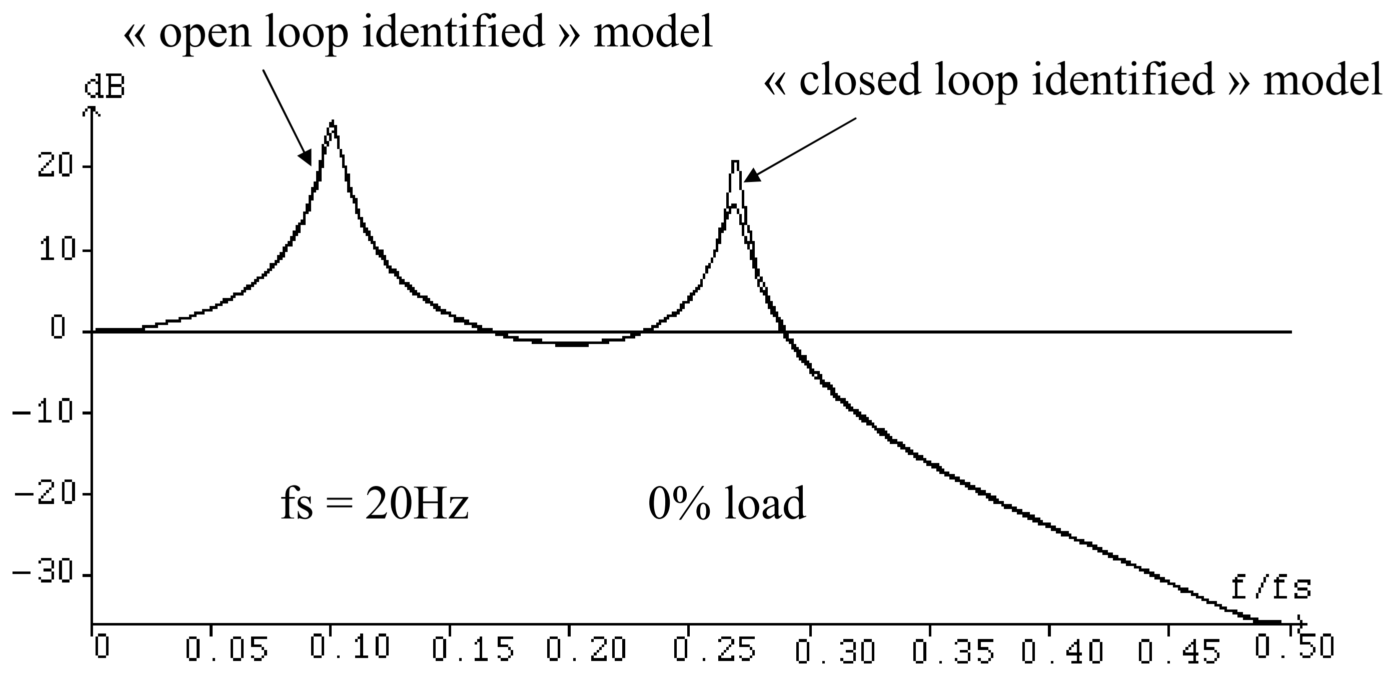
*Cannot be dissociated from the controller and robustness issues*

# Identification in Closed Loop

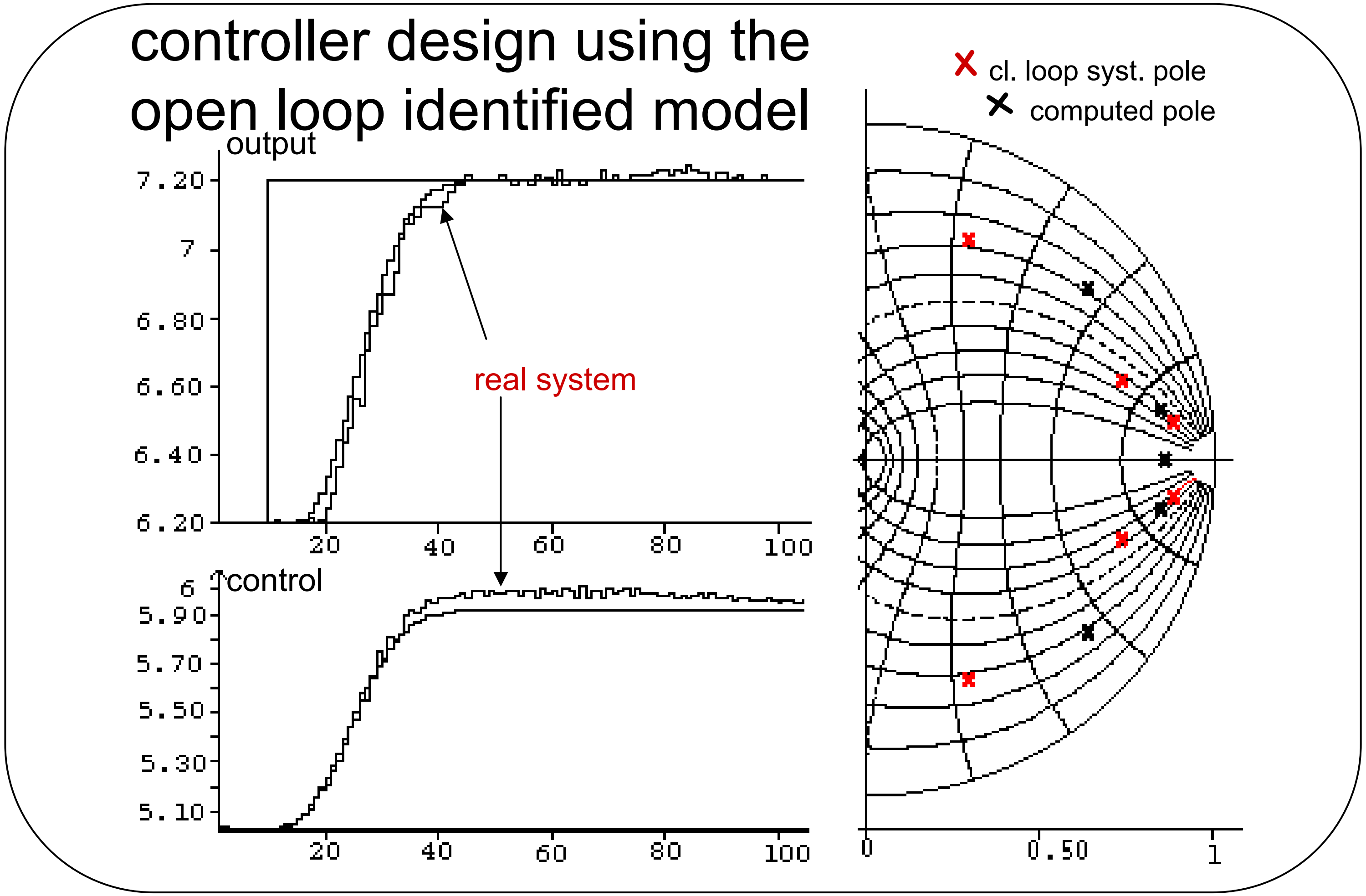
The flexible transmission



# What is the *good* model ?



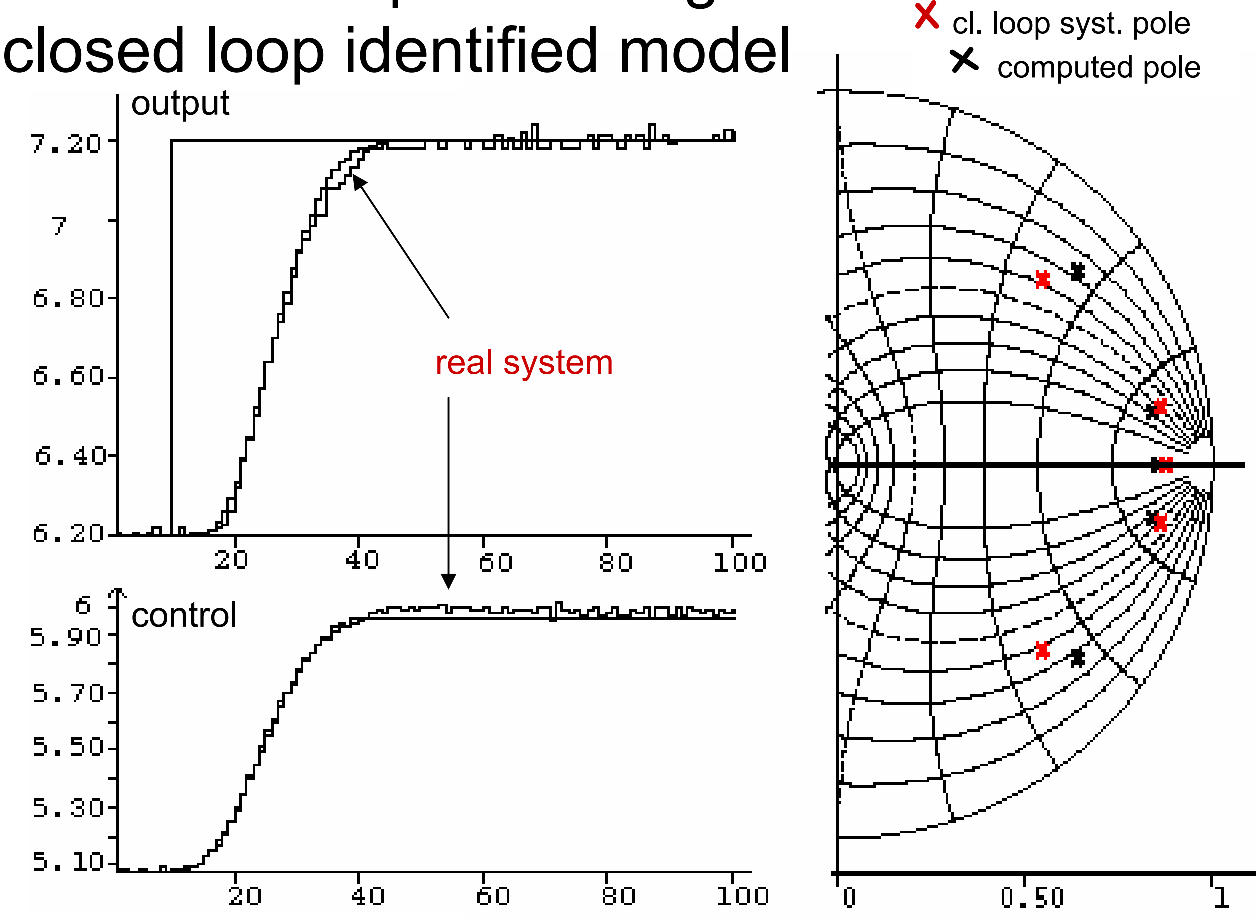
# Benefits of identification in closed loop (1)




The pattern of *identified closed loop poles* is different from the pattern of *computed closed loop poles*

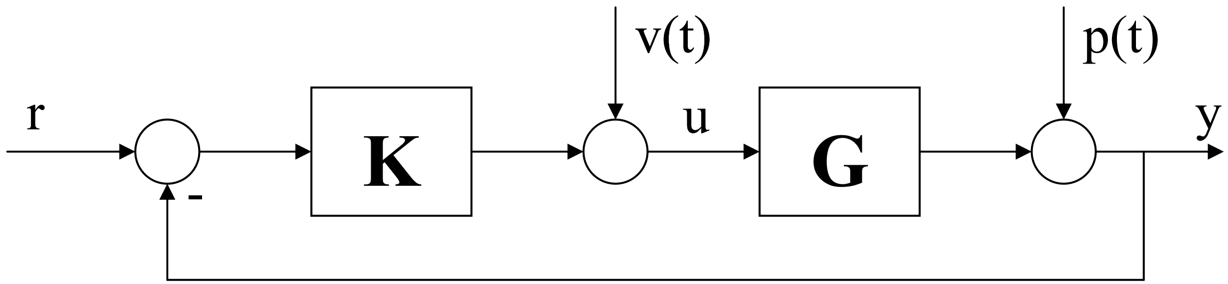
# Benefits of identification in closed loop (2)

controller computed using the closed loop identified model




The *computed* and the *identified* closed loop poles are very close

# Notations




$$G(q^{-1}) = \frac{q^{-d}B(q^{-1})}{A(q^{-1})} \qquad K(q^{-1}) = \frac{R(q^{-1})}{S(q^{-1})}$$

Sensitivity functions :

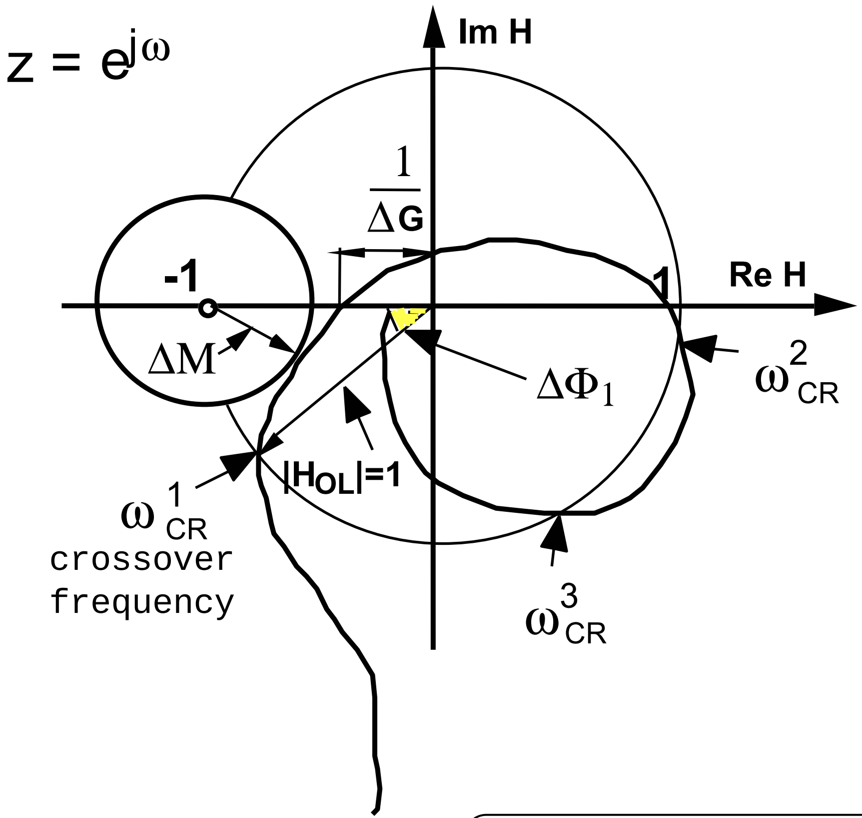
$$S_{yp}(z^{-1}) = \frac{1}{1+KG} \;;\; S_{up}(z^{-1}) = -\frac{K}{1+KG} \;;\; S_{yv}(z^{-1}) = \frac{G}{1+KG} \;;\; S_{yr}(z^{-1}) = \frac{KG}{1+KG}$$

Closed loop poles : $P(z^{-1}) = A(z^{-1})S(z^{-1}) + z^{-d}B(z^{-1})R(z^{-1})$

*True closed loop system* :(K,G), P, $S_{xy}$

*Nominal simulated(estimated) closed loop* :$(K, \hat{G}), \hat{P}, \hat{S}_{xy}$

# Robustness Margins




Typical values:

$\Delta M \geq 0.5$ (-6dB), $\Delta\tau > T_S$

$\Delta M \geq 0.5 \Rightarrow \Delta G \geq 2$ ; $\Delta\Phi > 29°$

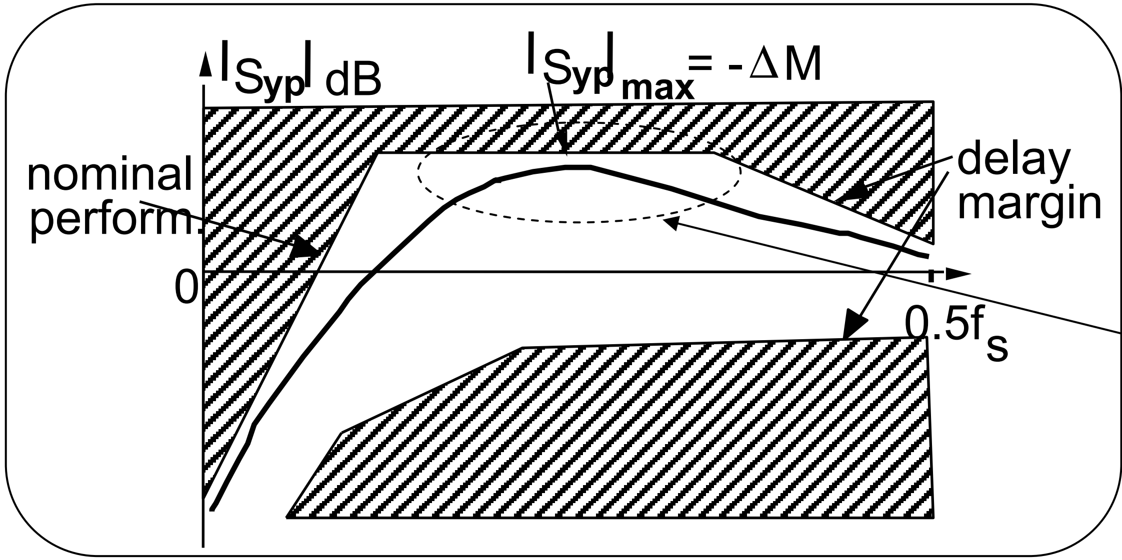
*The inverse is not necessarily true!*

Critical frequency region for control

Modulus Margin: $\Delta M = \left|1+H_{OL}(z^{-1})\right|_{min} = \left(\left|S_{yp}(z^{-1})\right|_{max}\right)^{-1} = \left(\|S_{yp}\|_{\infty}\right)^{-1}$

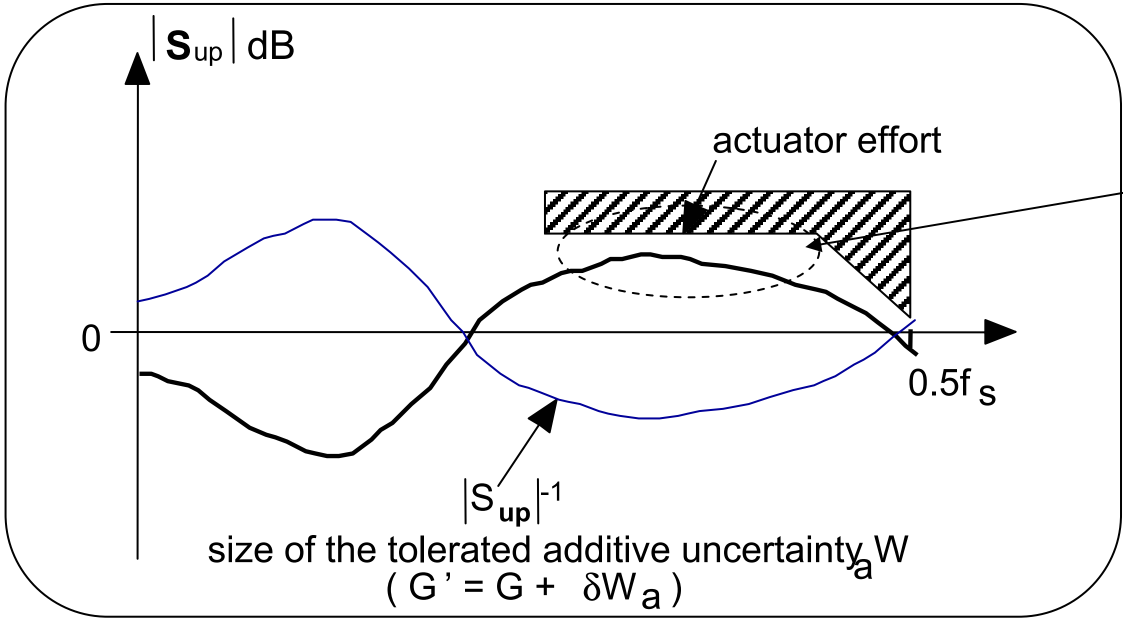
Delay Margin: $\Delta\tau = \min_i \frac{\Delta\Phi_i}{\omega^i_{CR}}$

# Templates for the Sensitivity Functions




Output Sensitivity Function

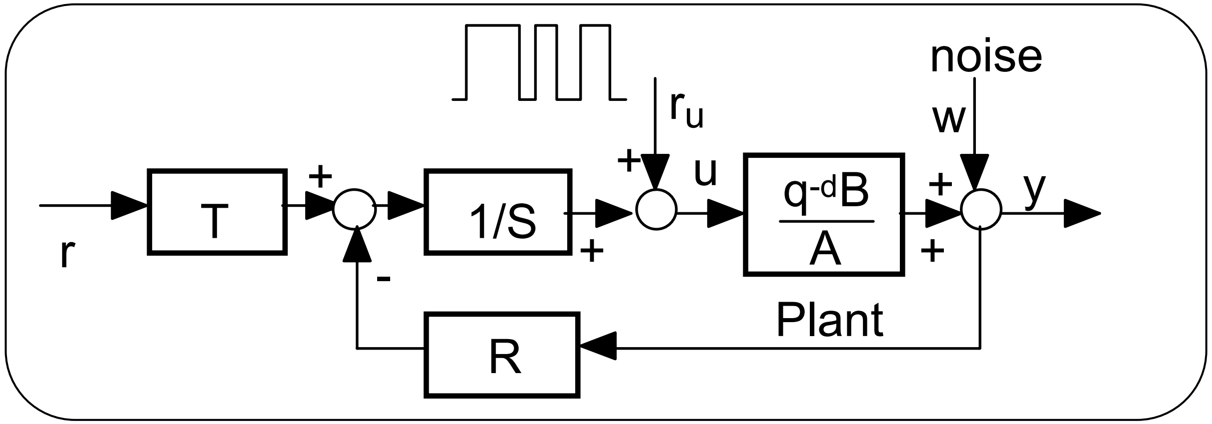
Critical frequency region for control



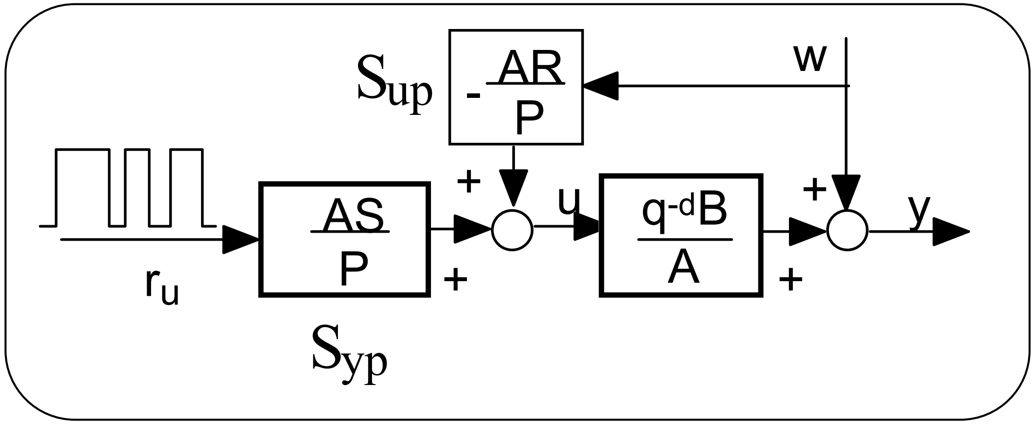

Critical frequency region for control

Input Sensitivity Function

# Identification in Closed Loop




Open loop interpetation



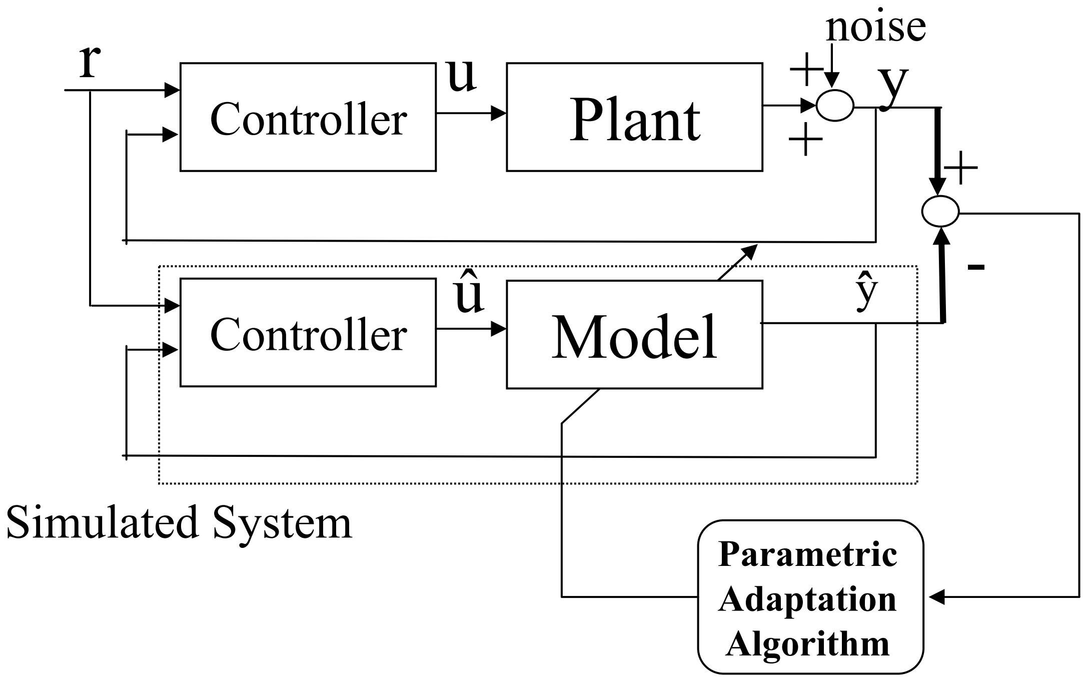

***Objective :*** development of algorithms which:

- take advantage of the « improved » input spectrum
- are insensitive to noise in closed loop operation

# Objective of the Identification in Closed Loop

(identification for control)

Find the « plant model » which minimizes the discrepancy between the « real » closed loop system and the « simulated » closed loop system.

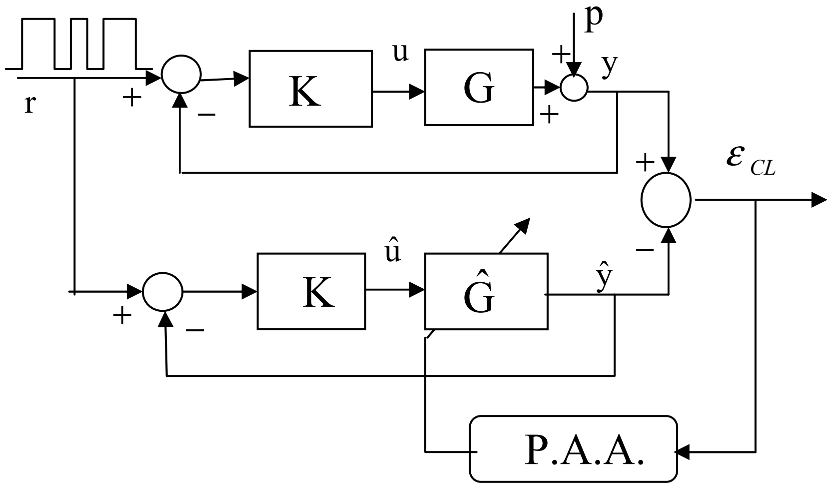



**CLOE Algorithms**

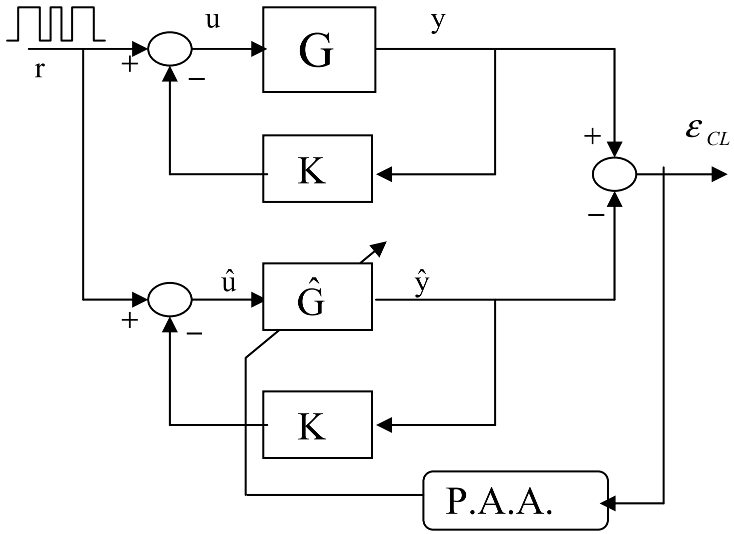
Closed Loop Output Error

# Closed Loop Output Error Identification Algorithms (CLOE)

Excitation added to reference signal

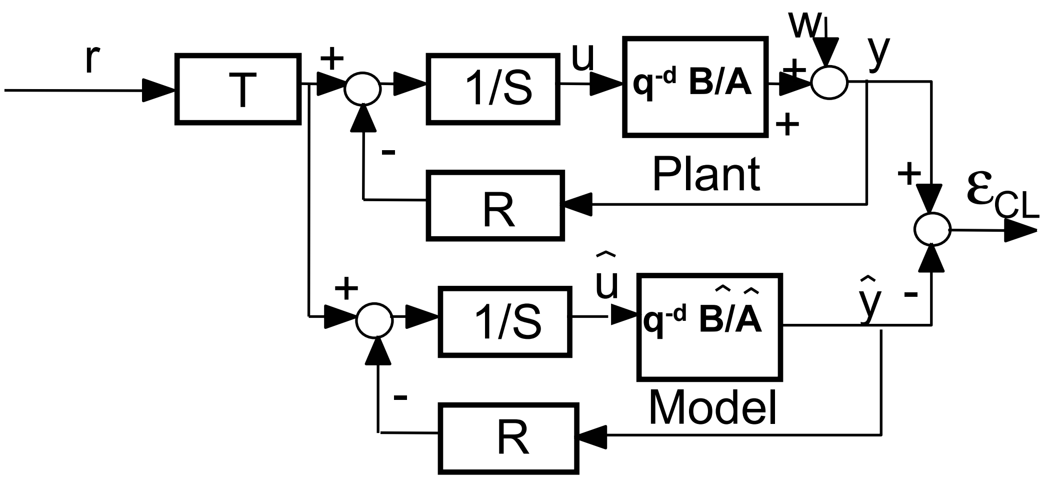



Excitation added to controller output




*Same algorithm but different properties of the estimated model*

# Iterative Identification in Closed Loop and Controller Re-Design




*Step 1 : Identification in Closed Loop*

-Keep controller constant

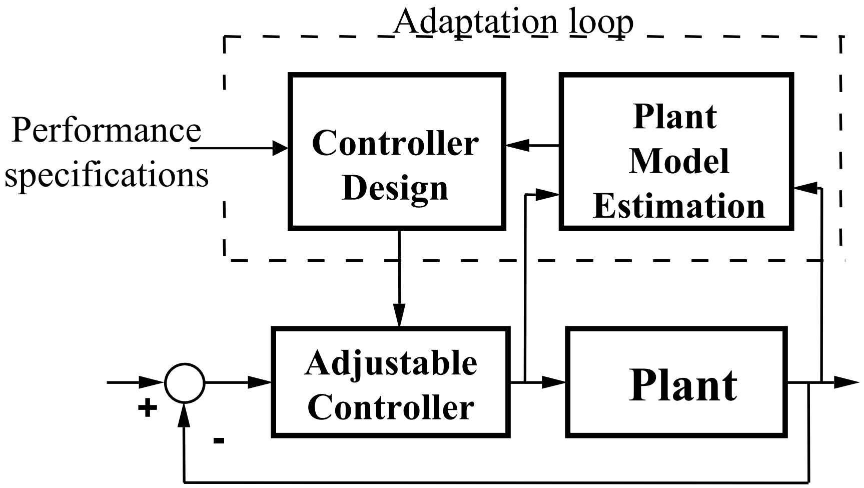
-Identify a new model such that $\varepsilon_{CL} \searrow$

*Step 2 : Controller Re – Design*

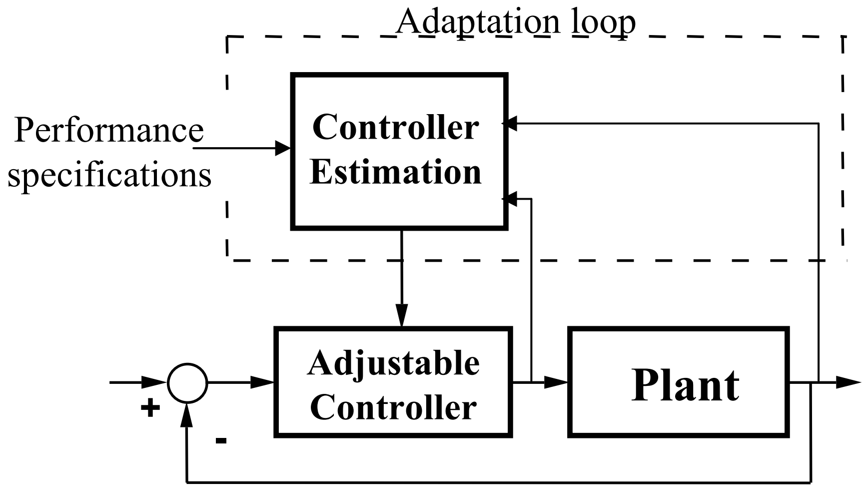
- Compute a new controller such that $\varepsilon_{CL} \searrow$

Repeat 1, 2, 1, 2, 1, 2,…

# Adaptive Control – Basic Schemes



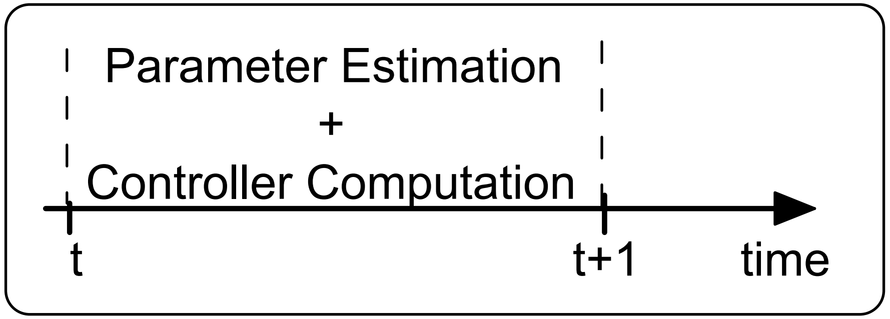

Indirect Adaptive Control

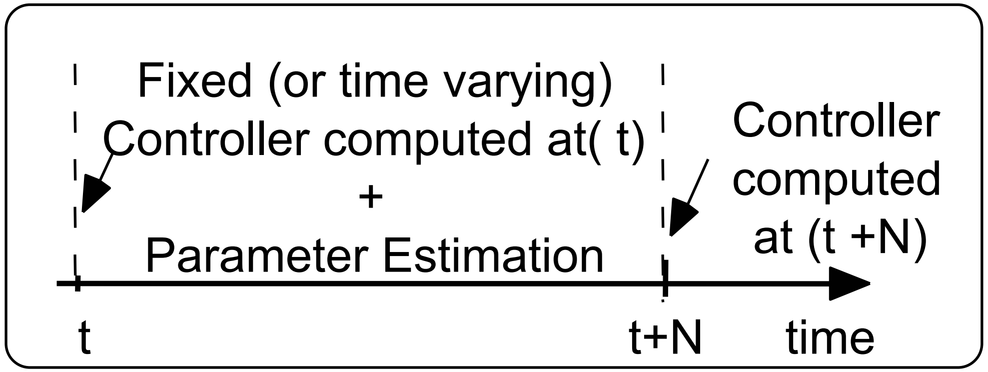



Direct Adaptive Control

- Indirect adaptive control
- Direct adaptive control *(the controller is directly estimated)*

# Iterative Identification and Controller Redesign versus (Indirect) Adaptive Control



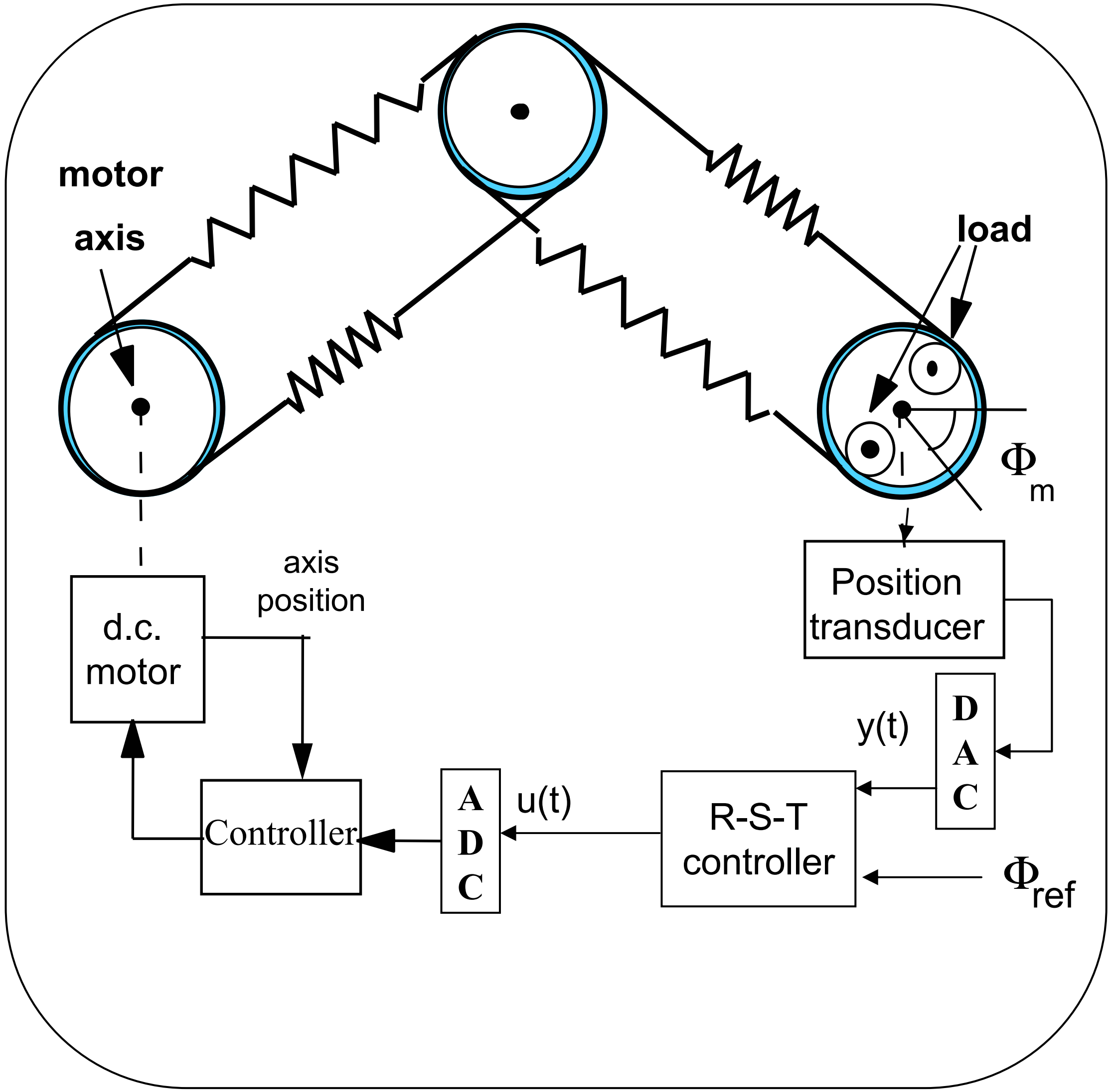

$N = 1$ : Adaptive Control

$N = Small$
Adaptive Control
$N = Large$
Iterative Identification in C.L.
And Controller Re-design
$N \Rightarrow \infty$
Plant Identification in C.L. +
Controller Re-design

The *iterative procedure* introduces a time scale separation between identification / control design

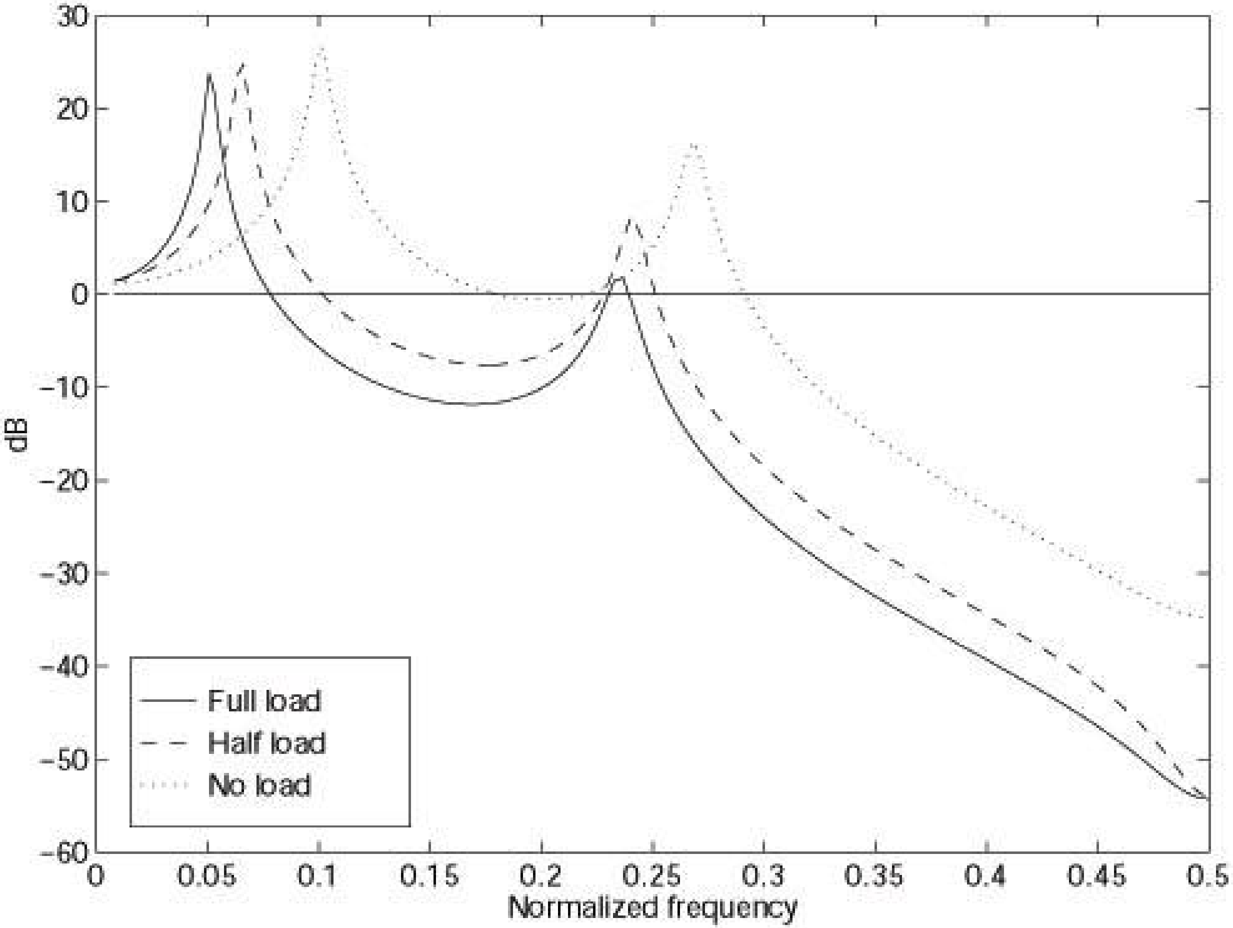
# Adaptive Control of a Flexible Transmission

The flexible transmission



# Adaptive Control of a Flexible Transmission

Frequency characteristics for various load




*Rem.:* the main vibration mode varies by 100%

# Robust Control Design for Adaptive Control

**parameter variations** (low frequency) → **Adaptation**

**unstructured uncertainities** (high frequency) → **Robust Design**

**Basic rule** : The *input sensitivity function* ($S_{up}$) should be small in medium and high frequencies

*How to achieve this ?*

**Pole Placement :**

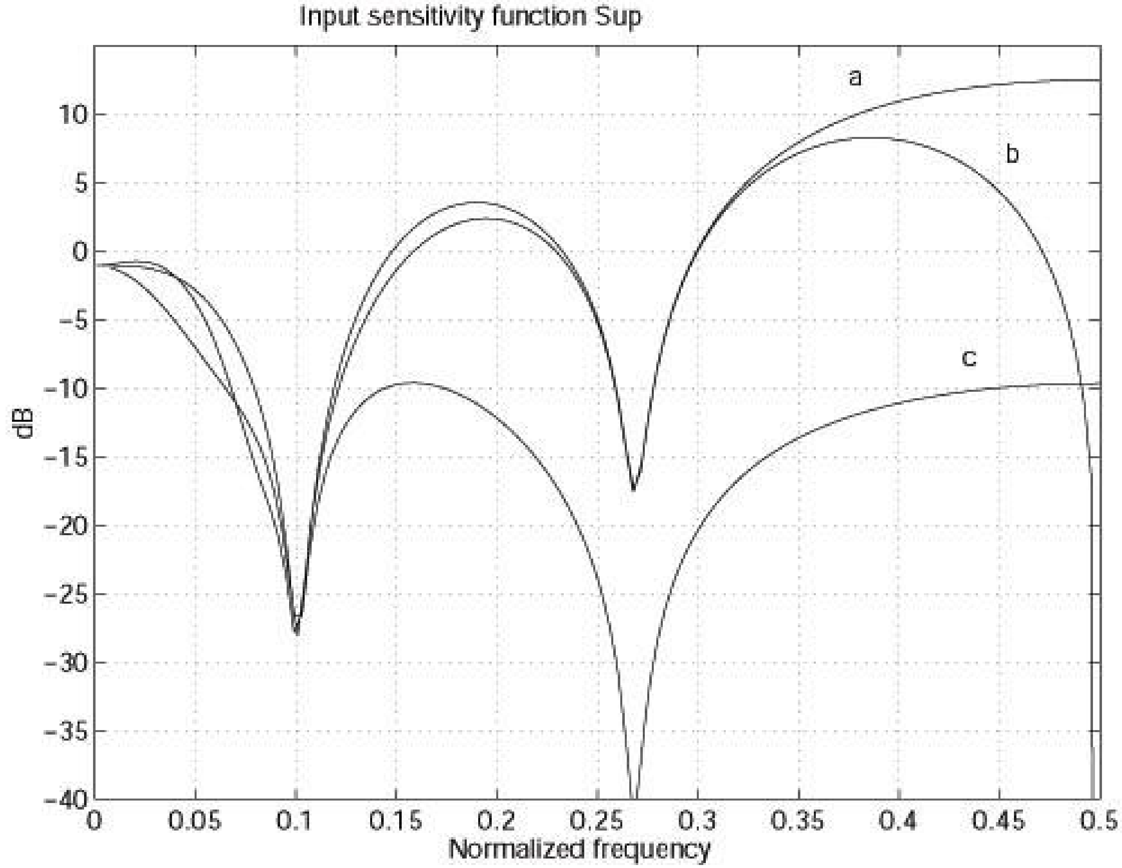
- Opening the loop in high frequncies (at $0.5f_s$)
- Placing auxiliary closed loop poles near the high frequency poles of the plant model

**Generalized Predictive Control :**

- Appropriate weighting filter on the control term in the criterion

# Robust Control Design for Adaptive Control

(Flexible Transmission)



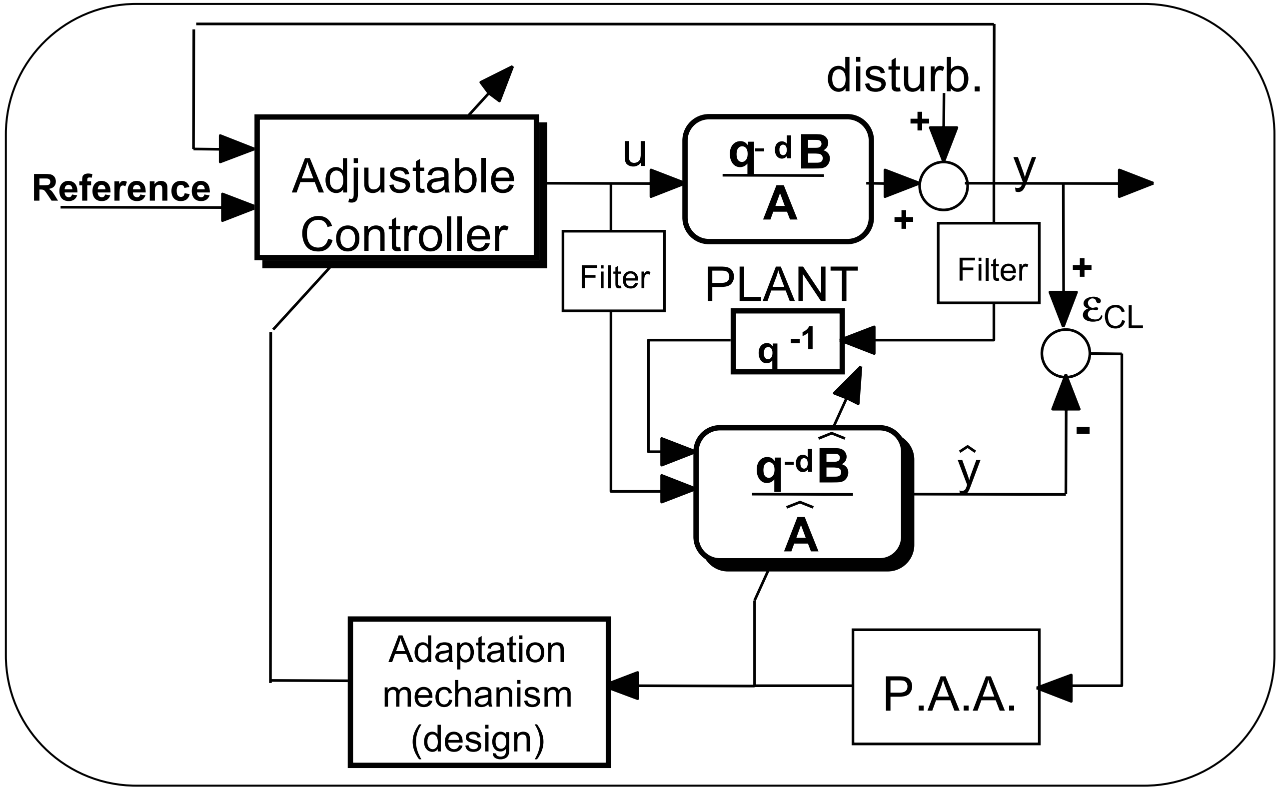

a) Standard pole placement (1 pair dominant poles + h.f. aperiodic poles)

b) Opening the loop at $0.5f_S$ ($H_R = 1 + q^{-1}$)

c) Auxiliary closed loop poles near high frequency plant poles

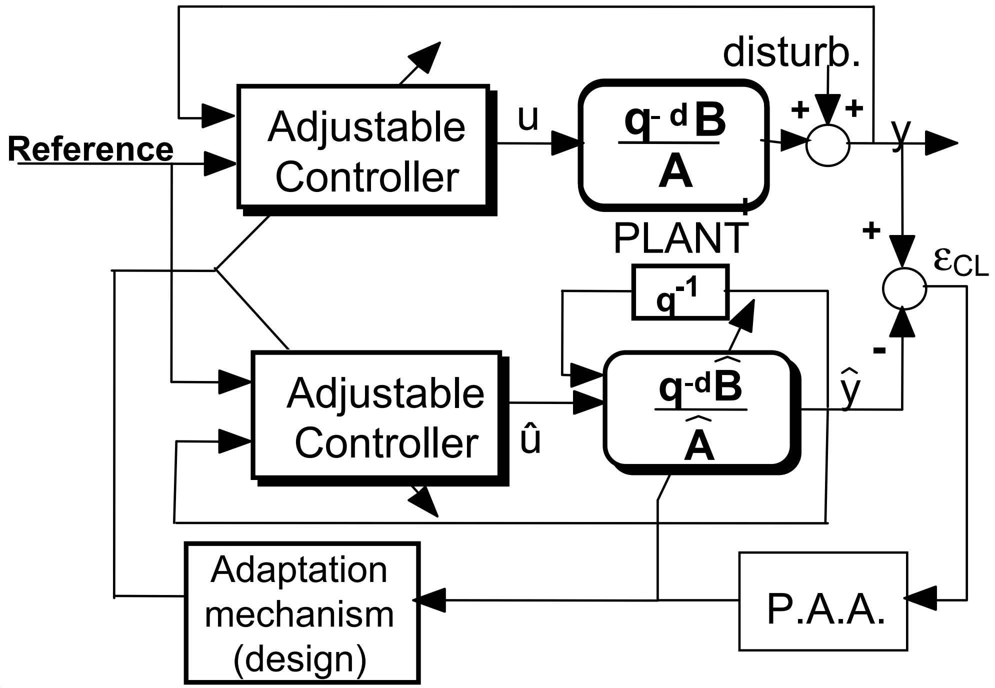
# Parameter Estimators for Adaptive Control

# Classical Indirect Adaptive Control




- Uses R.L.S. type estimator (equation error)
- Sensitive to output disturbances
- Requires « adaptation freezing » in the absence of persistent excitation
- The threshhold for « adaptation freezing » is problem dependent

# Closed Loop Output Error Parameter Estimator for Adaptive Control

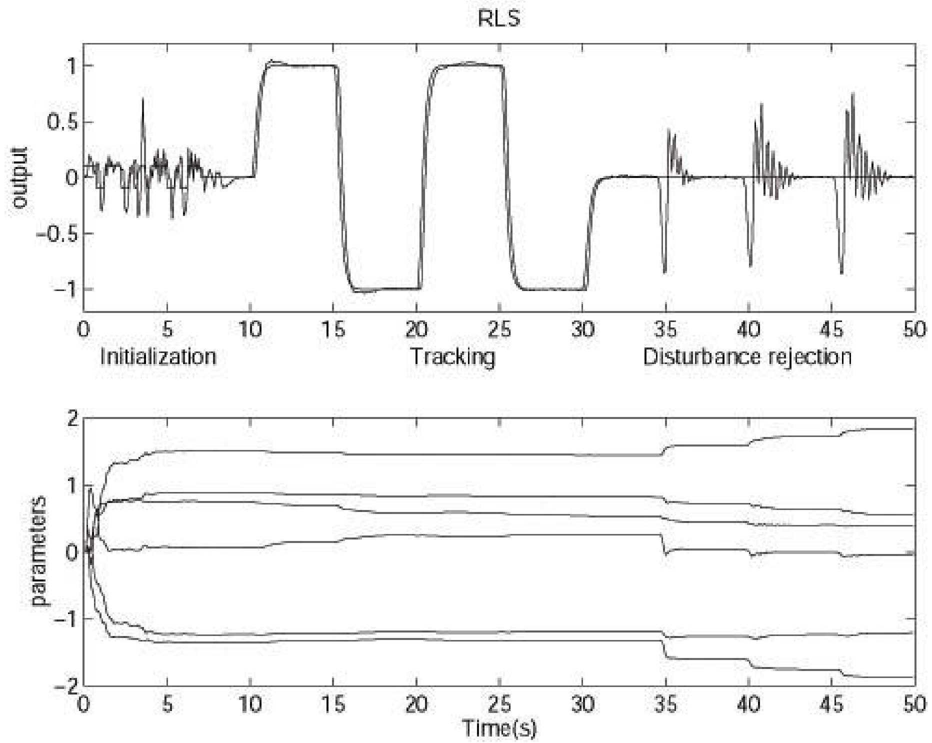


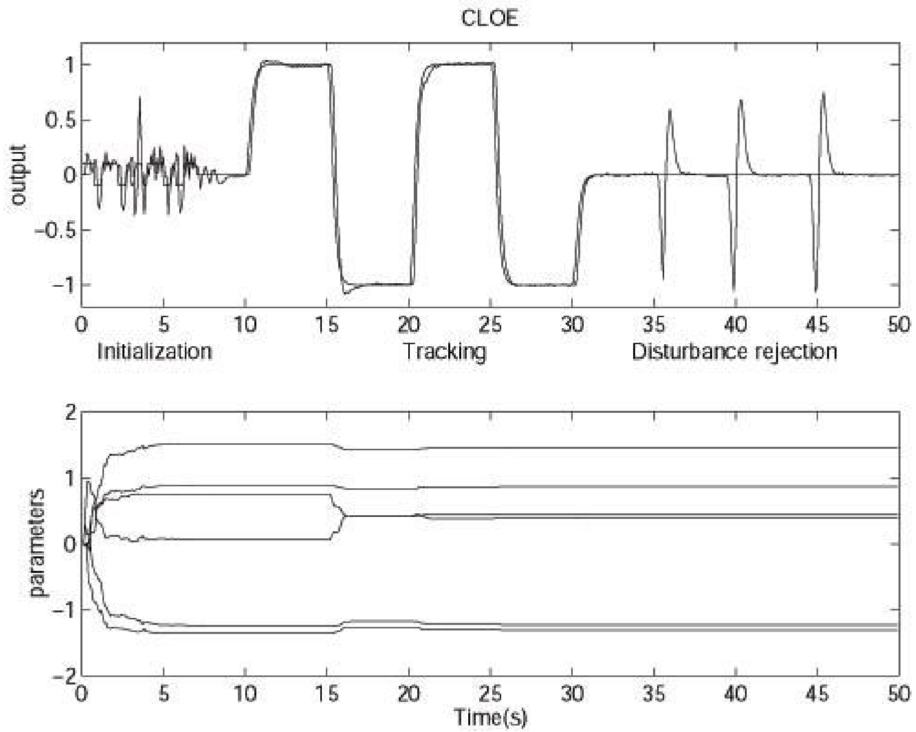

- Insensitive to output disturbances
- Remove the need for « adaptation freezing » in the absence of persistent excitation
- CLOE requires stability of the closed loop
- Well suited for « adaptive control with multiple models »

# Adaptive Control – Effect of Disturbances

Classical parameter estimator
(filtered RLS)

CLOE parameter estimator

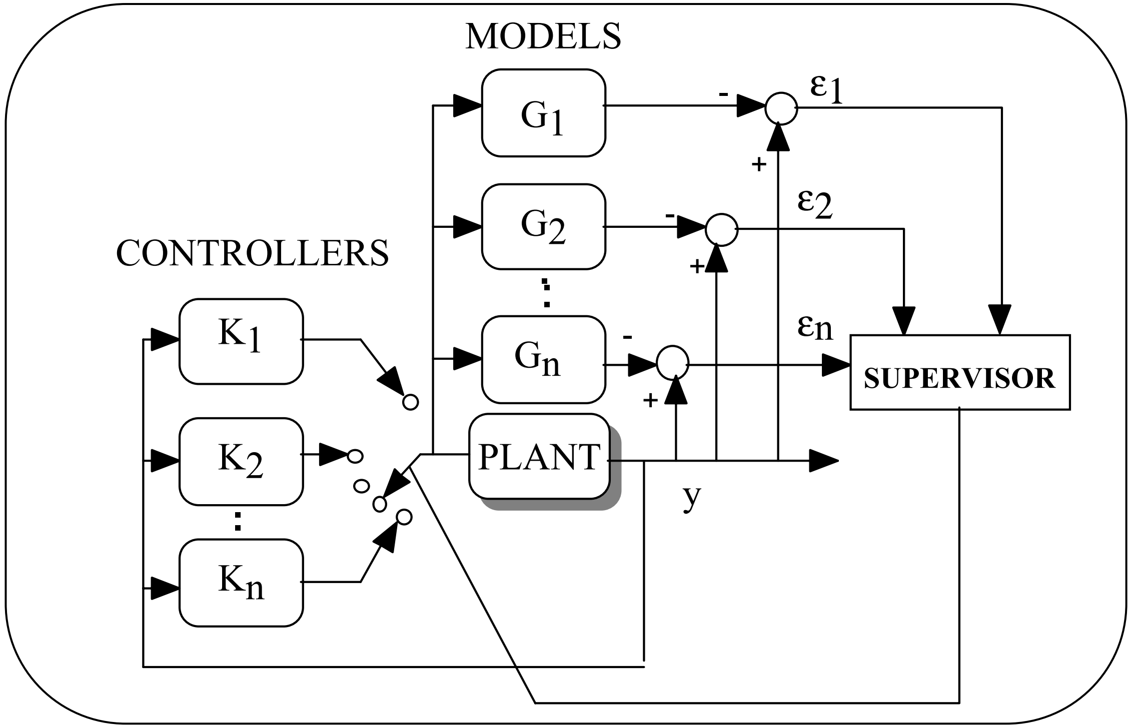



*Disturbances destabilize the adaptive system when using RLS parameter estimator (in the absence of a variable reference signal)*

# Adaptive Control with Multiple Models

# Supervisory Control



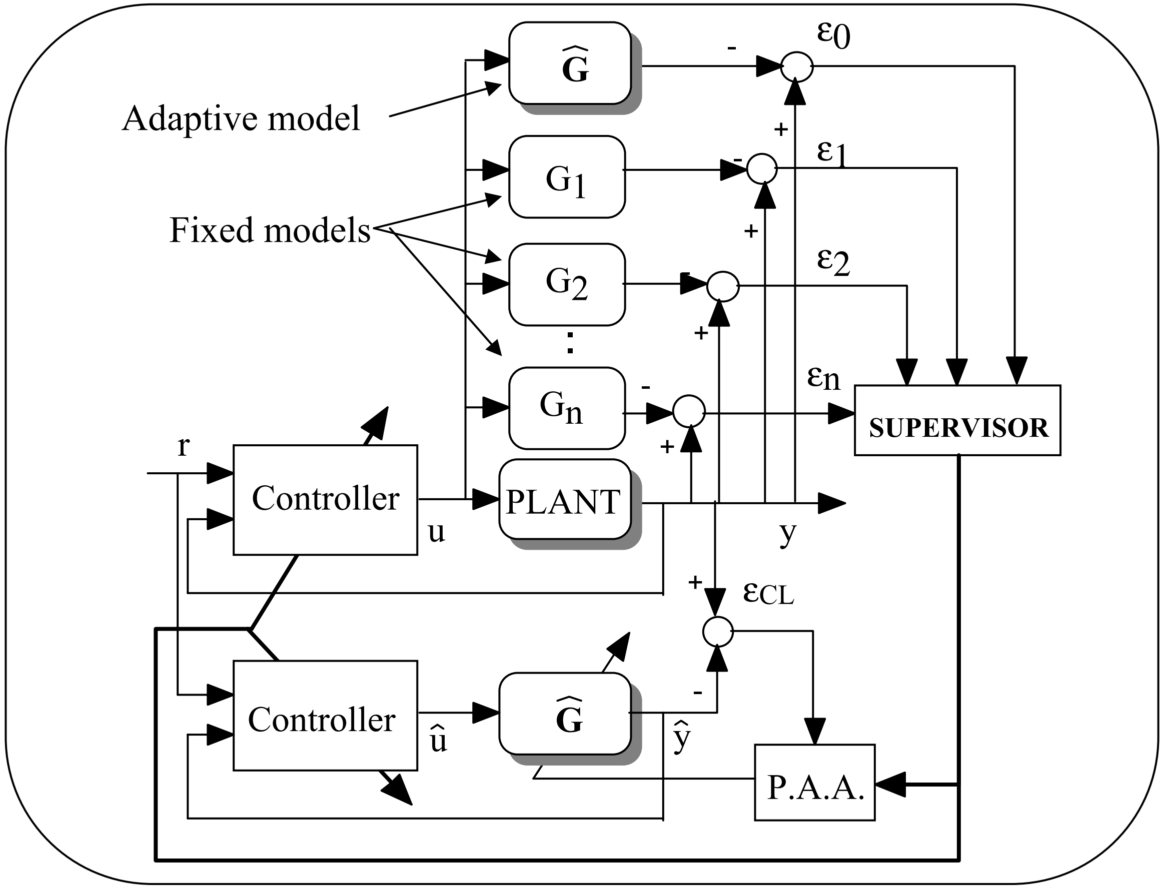

Performance criterion:

$$J_i(t) = \alpha\varepsilon_i^2(t) + \beta \sum_{j=0}^{t} e^{-\lambda(t-j)}\varepsilon_i^2(j) ; \alpha \geq 0 , \beta \geq 0 , i = 1,2 \ldots n$$

Switching rule: $\min_i J_i(t)$

Rem. : *stability requires the use of hysteresis or time delay in switching*

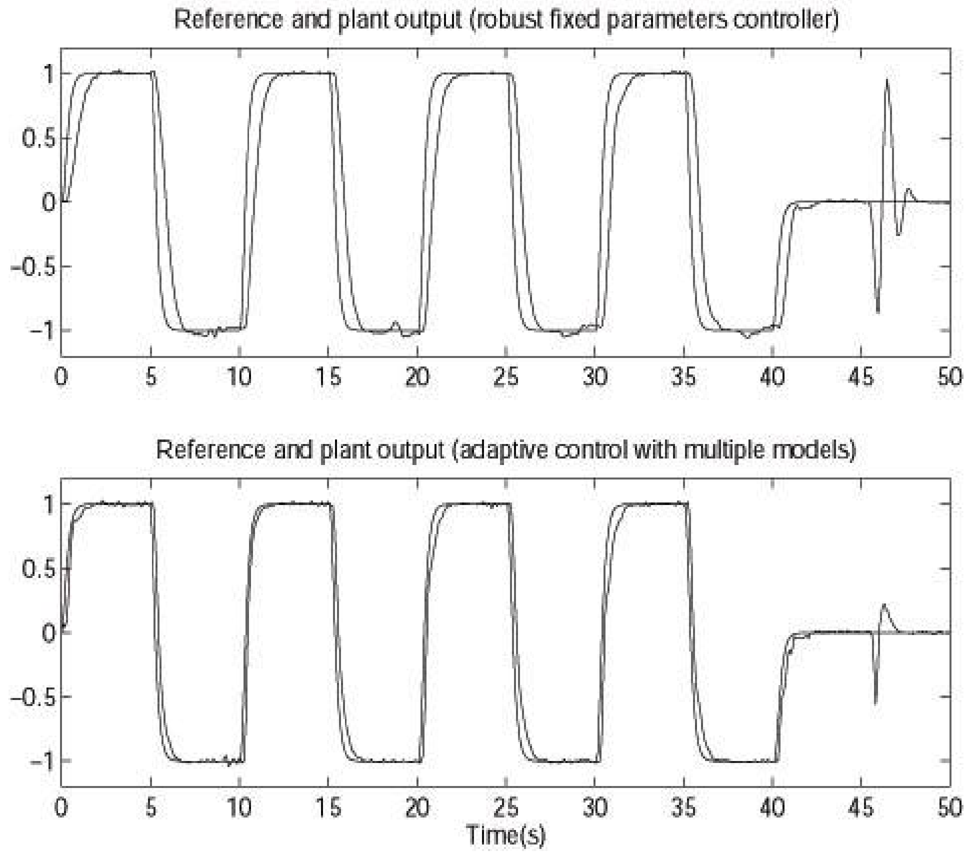
# Adaptive Control with Multiple Models




n is small (for the flexible transmission n = 3)

Multiple models : *improvement of the adaptation transients*
CLOE Estimator : *reduction of the false swithchings, performance improvement*

# Adaptive Control versus Robust Control

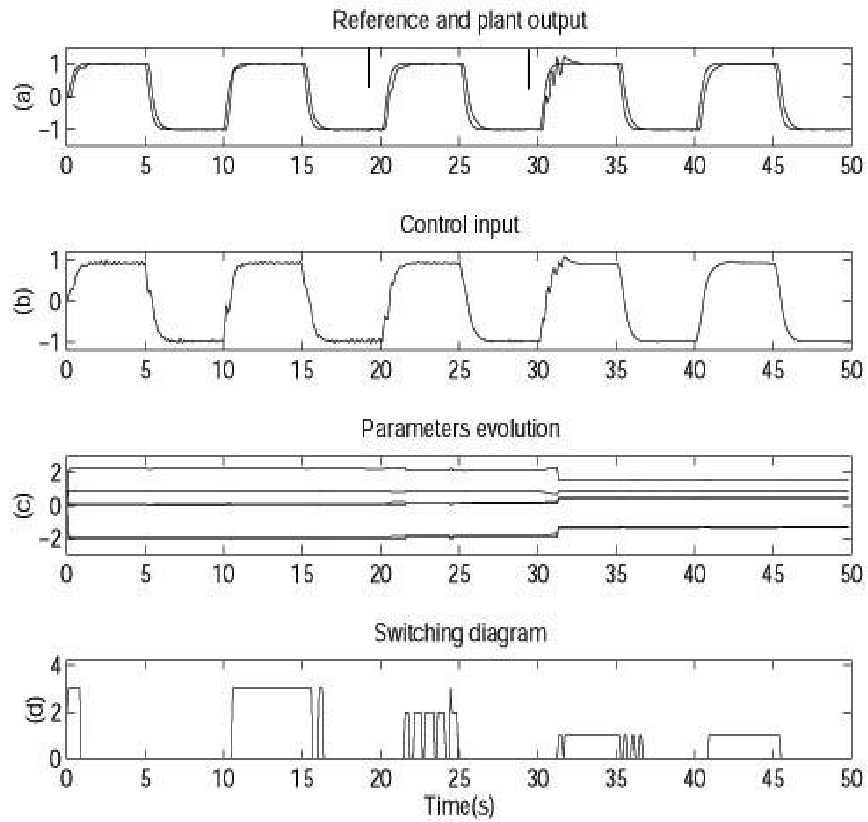



Load variations : 0% → 100% (in several steps)

*Rem* : The robust controller used is the winner of an international benchmark test for robust control of the flexible transmission (EJC, no.2., 1995)

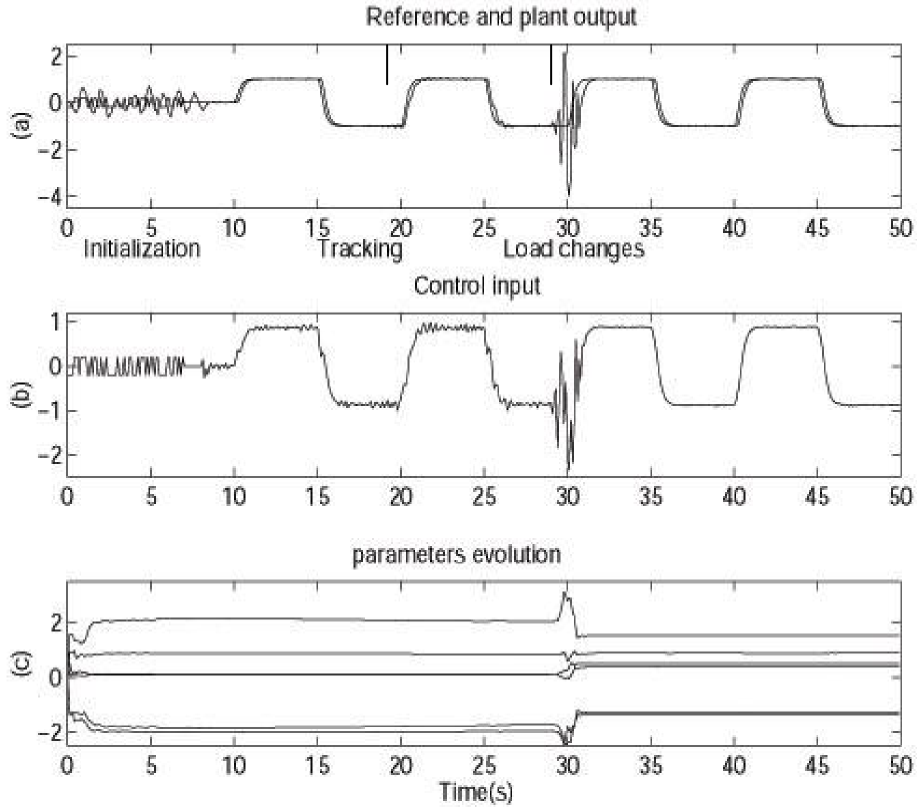
# Adaptation Transients

Adaptive Control with Multiple Models




**0 = adaptive ; 1= 0% ; 2 = 50% ; 3 = 100%**

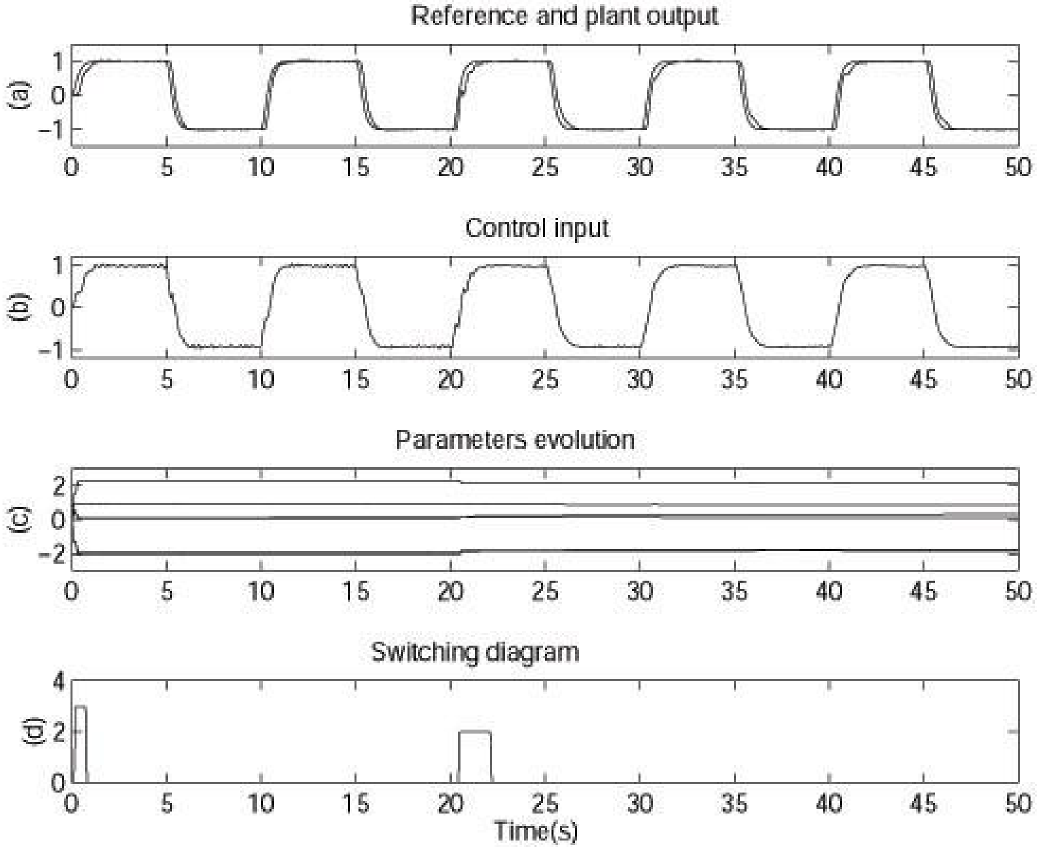
Classical Adaptive Control (simulation)




Load variations : 100% → 0% (in two steps at 19s and 29s)

# Adaptive Control with Multiple Models

The « plant models » are not in the « model set »




**0 = adaptive ; 1= 0% ; 2 = 50% ; 3 = 100%**

Load variations : 75% → 25%

# **Adaptive rejection of unknown disturbances**
## ***Application to active suspension***

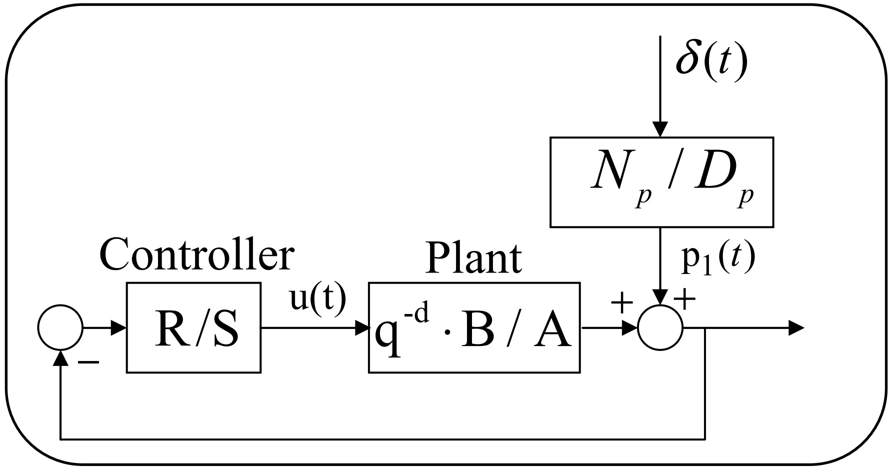
# Rejection of unknown disturbances

- **Problem:** Attenuation of unknown and/or variable stationary disturbances without using an additional measurement
- **Solution:** Direct adaptive feedback control
- **Methodology:** Based on the
  - Internal model principle
  - Sensitivity function
  - Q - parametrization
  - Direct adaptive control algorithm
- **Objective:** Computation of a controller with an adaptive internal model of the disturbance

Hypothesis: *Plant model parameters are constant and known*

Rem: *Stationary disturbances models have poles on the unit circle*

# Closed loop system. Notations




$$p_1(t) = \frac{N_p(q^{-1})}{D_p(q^{-1})} \cdot \delta(t): \text{deterministic disturbance}$$

$D_p \rightarrow$ poles on the unit circle; $\delta(t) = \text{Dirac}$

Controller :

$$R(q^{-1}) = R'(q^{-1}) \cdot H_R(q^{-1});$$

$$S(q^{-1}) = S'(q^{-1}) \cdot H_S(q^{-1}).$$

## Internal model principle: $H_S(z^{-1}) = D_p(z^{-1})$

Output : $y(t) = \dfrac{A(q^{-1})S(q^{-1})}{P(q^{-1})} \cdot p_1(t) = S_{yp}(q^{-1}) \cdot p_1(t)$

CL poles : $P(q^{-1}) = A(q^{-1})S(q^{-1}) + z^{-d}B(q^{-1})R(q^{-1})$

$\rightarrow$ $y(t) = \dfrac{A(q^{-1})H_S(q^{-1})S'(q^{-1})N_p(q^{-1})}{P(q^{-1})} \cdot \dfrac{1}{D_p(q^{-1})} \cdot \delta(t)$

# Direct adaptative control (Q-parameterization)

Central contr: $[R_0(q^{-1}),S_0(q^{-1})]$.

Bezout: $P(q^{-1})=A(q^{-1})S_0(q^{-1})+q^{-d}B(q^{-1})R_0(q^{-1})$.

Control: $S_0(q^{-1})\, u(t) = -R_0\,(q^{-1})\, y(t)$

**Q-parameterization** :

$\mathbf{R(z^{1})=R_0(q^{-1})+A(q^{-1})Q(q^{-1});}$

$\mathbf{S(q^{-1})=S_0(z^{-1})-q^{-d}B(q^{-1})Q(q^{-1}).}$

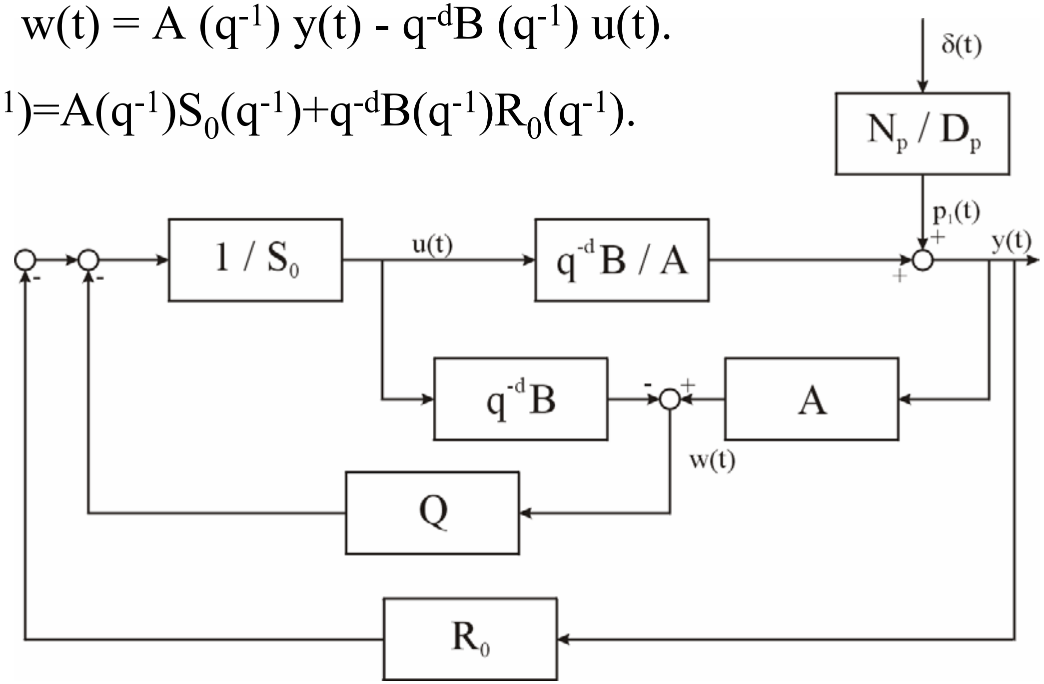
$Q(q^{-1})$ computed such as $[R(q^{-1}),S(q^{-1})]$ contain the internal model of the disturb.

$$S_0 - q^{-d}BQ = MD_p$$

Control: $S_0(q^{-1})\, u(t) = -R_0\,(q^{-1})\, y(t) - Q\,(q^{-1})\, w(t)$,

where $w(t) = A\,(q^{-1})\, y(t) - q^{-d}B\,(q^{-1})\, u(t)$.

CL poles: $P(q^{-1})=A(q^{-1})S_0(q^{-1})+q^{-d}B(q^{-1})R_0(q^{-1})$.




The internal model can be tuned with Q

## Direct Adaptive Control (unknown $D_p$)

(Based on an ideea of Y. Z. Tsypkin)

**Hypothesis:** Identified (known) plant model (A,B,d).

**Goal:** minimize y(t) (according to a certain criterion).

Consider $p_1(t) = \dfrac{N_p(q^{-1})}{D_p(q^{-1})} \cdot \delta(t)$ : deterministic disturbance.

$$y(t) = \frac{A(q^{-1})\left[S_0(q^{-1}) - q^{-d}B(q^{-1})Q(q^{-1})\right]}{P(q^{-1})} \cdot \frac{N_p(q^{-1})}{D_p(q^{-1})} \cdot \delta(t) = \frac{\left[S_0(q^{-1}) - q^{-d}B(q^{-1})Q(q^{-1})\right]}{P(q^{-1})} w(t)$$

$$\varepsilon(t) = \frac{S_0(q^{-1})}{P(q^{-1})} \cdot w(t) - \frac{q^{-d}B(q^{-1})}{P(q^{-1})} Q(q^{-1}) \cdot w(t).$$

Let $\hat{Q}(t,q^{-1})$ be an estimated value of $Q(q^{-1})$

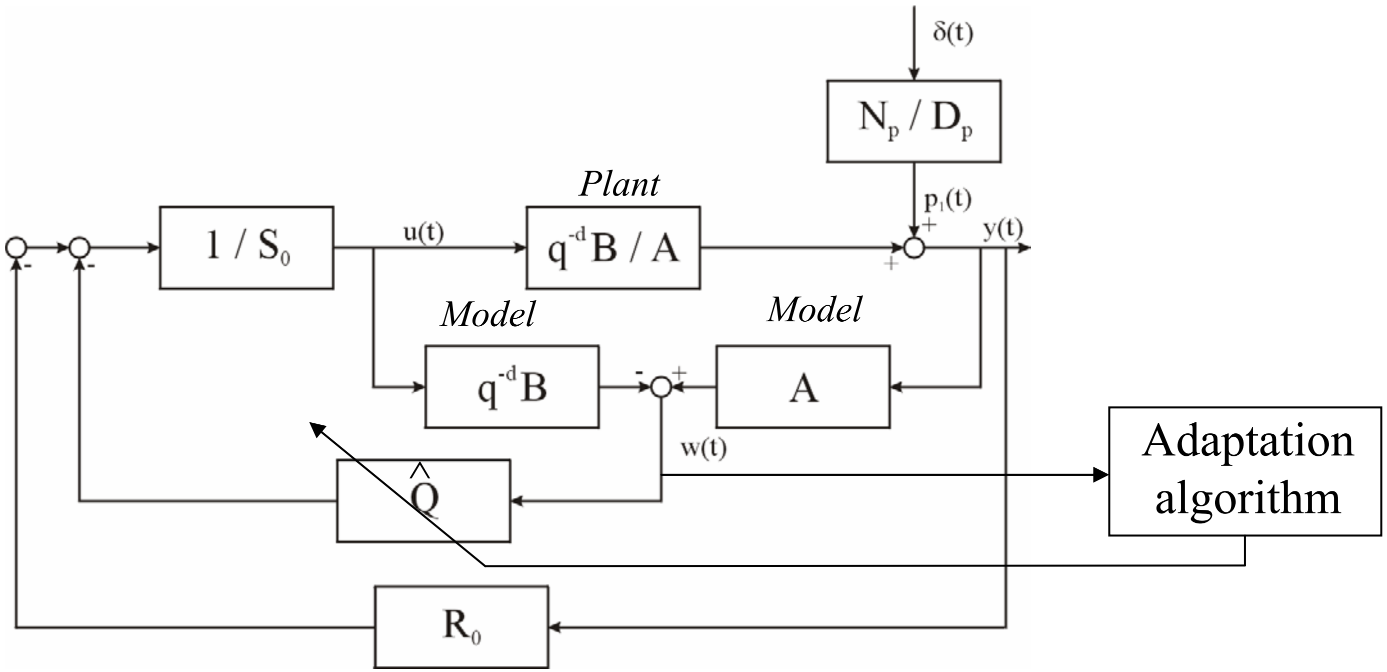
We can show that

Leads to a direct adaptive control →

$$\boxed{\varepsilon(t+1) = [Q(q^{-1}) - \hat{Q}(t+1,q^{-1})] \cdot \frac{q^{-d}B^*(q^{-1})}{P(q^{-1})} \cdot w(t) + v(t+1)}$$

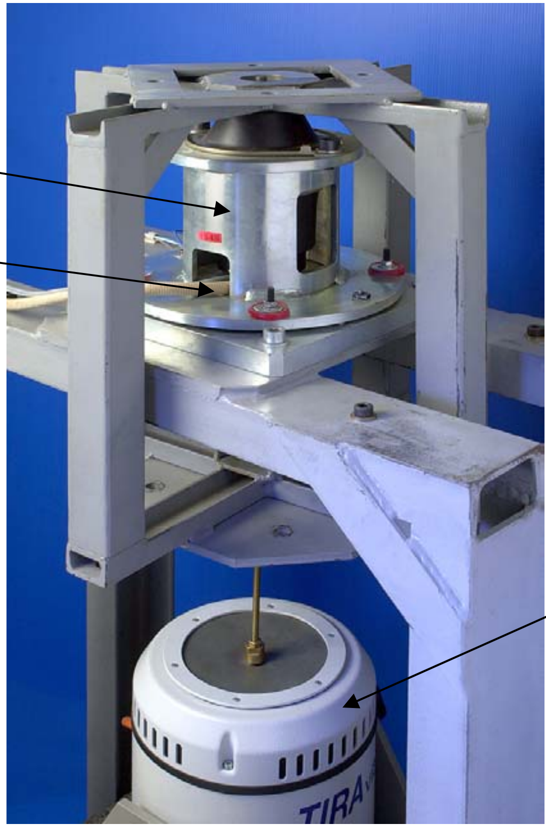
($v(t+1)$ = disturbance term $\rightarrow 0$)

# Direct adaptive rejection of unknown disturbances

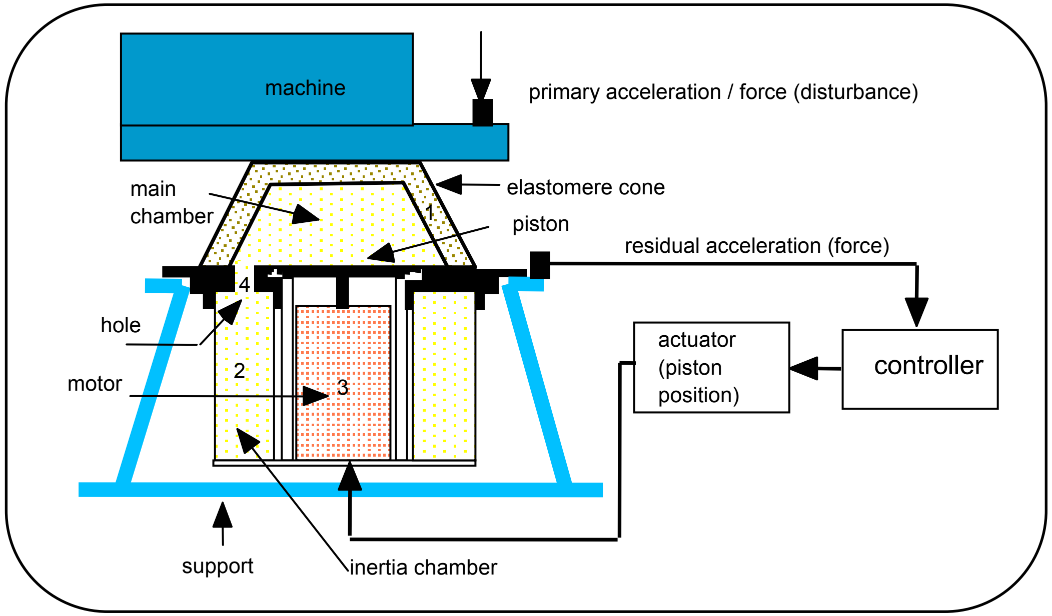



- *The order of the Q polynomial depends upon the order of the disturbance model denominator ($D_P$) and not upon the complexity of the plant model*
- *Less parameters to estimate than for the identification of the disturbance model*
- *Much simpler than "indirect adaptive control"*

# The Active Suspension

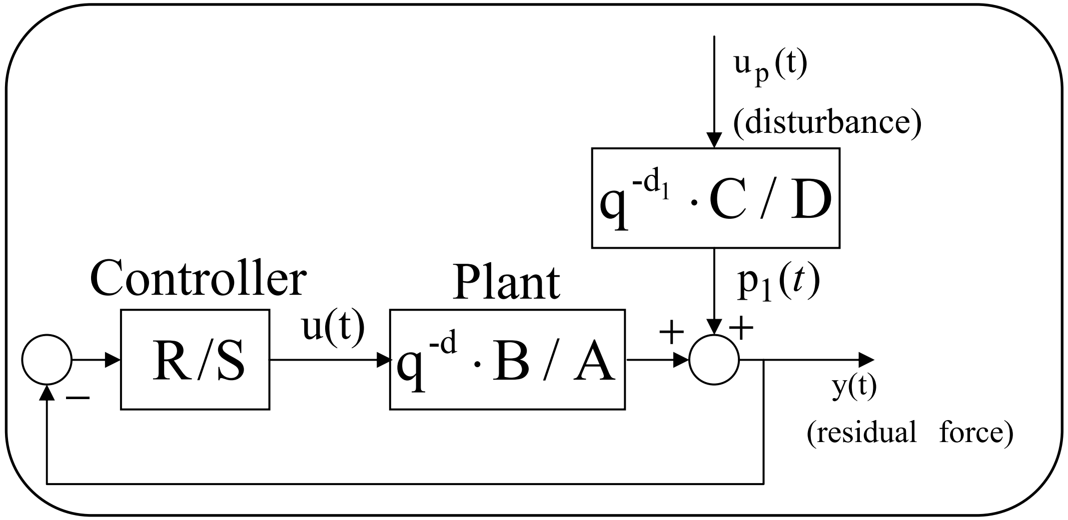



# The Active Suspension System




Two paths :

- Primary
- Secondary (double differentiator)



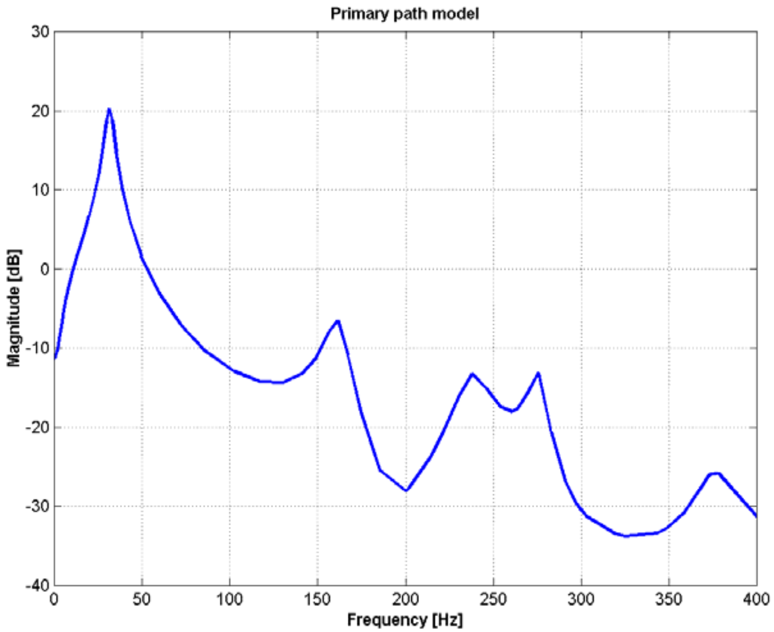

$$T_s = 0.00125\, s$$

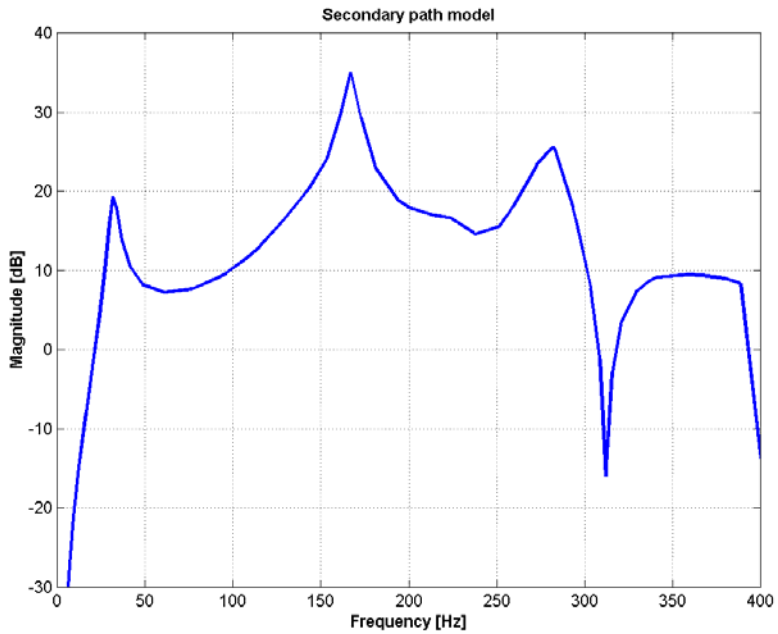
# Active Suspension

## Frequency Characteristics of the Identified Models

Primary path

Secondary path

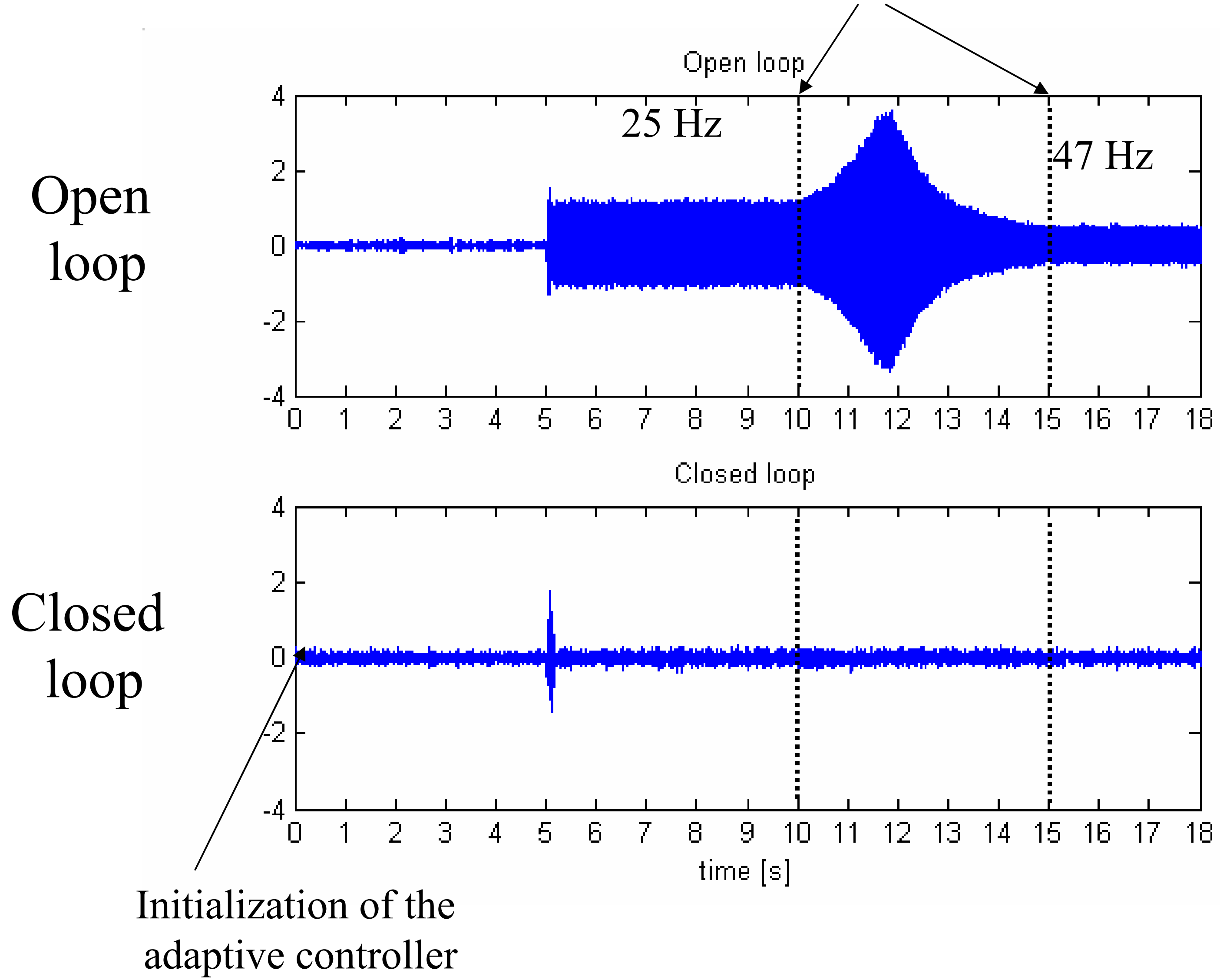



$$n_A = 14\,;\, n_B = 16\,;\, d = 0$$

# Adaptive disturbance rejection

Disturbance : Chirp



## Concluding Remarks

- Identification in closed loop establishes a bridge between robustness and adaptation

- *Iterative identification in closed loop and controller re-design* is a two times scales adaptive control

- Robust linear design in high frequency is needed for adaptive control schemes

- The « multiple models » approach to adaptive control improves significantly the adaptation transients

- Robust control gives hints for adaptive rejection of unknown disturbances

- High speed simple adaptive direct control scheme for rejection of unknown disturbances has been proposed and tested.

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**Commande des systèmes**

*conception,identification et mise en oeuvre*