Adaptive Control

Chapter 1: Introduction to Adaptive Control

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Abstract The aim of this introductory chapter is to emphasize the basic concepts pertinent to adaptive control and to present the significant adaptive control schemes. The final part of the chapter reviews briefly the various applications considered throughout the book.

Adaptive Control

A set of techniques for automatic adjustment of the controllers in *real time,* in order to achieve or to maintain a desired *level of performance* of the control system when the parameters of the plant (disturbance) dynamic model are unknown and/or change in time

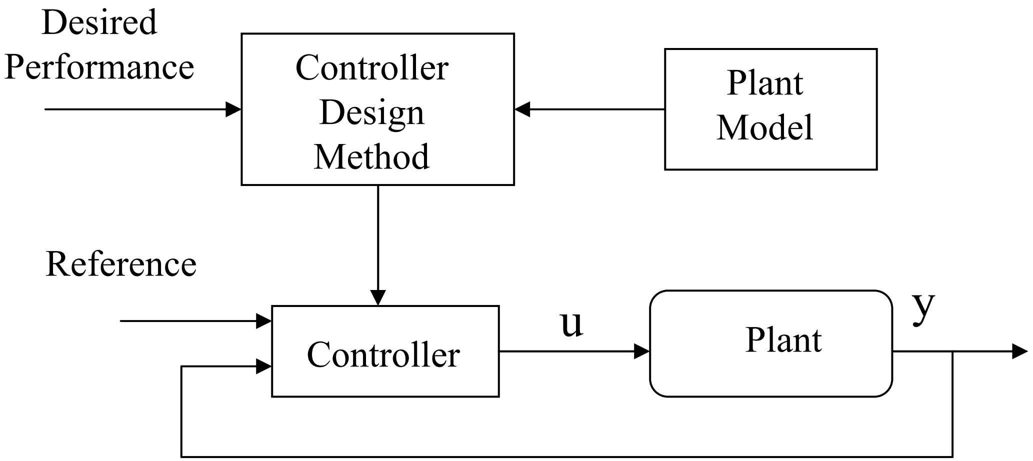
Particular cases:

1 Automatic tuning of the controllers for unknown but constant plant parameters
2 Unpredictable change of the plant (disturbance) model in time

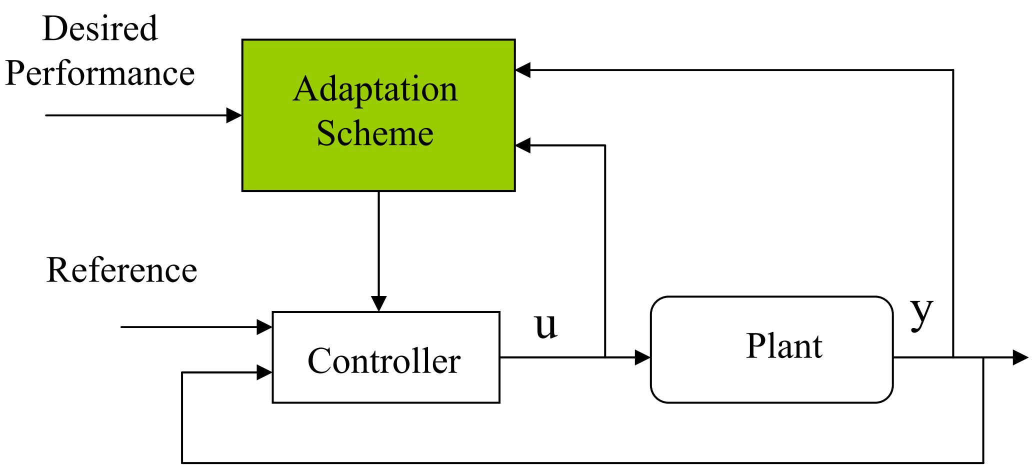
Outline

- Concepts
- Basic schemes
- Adaptive control versus Robust control
- Adaptive control configurations
  (open loop adaptation, direct and indirect adaptive control)
- Parameter adaptation algorithms
- RST digital controller
- Adaptive control: regimes of operation
- Identification in closed and controller redesign
- Adaptive regulation
- Use of *a priori* available information
- Adaptive control with multiple models
- Example of applications

Conceptual Structures



Principle of model based control design



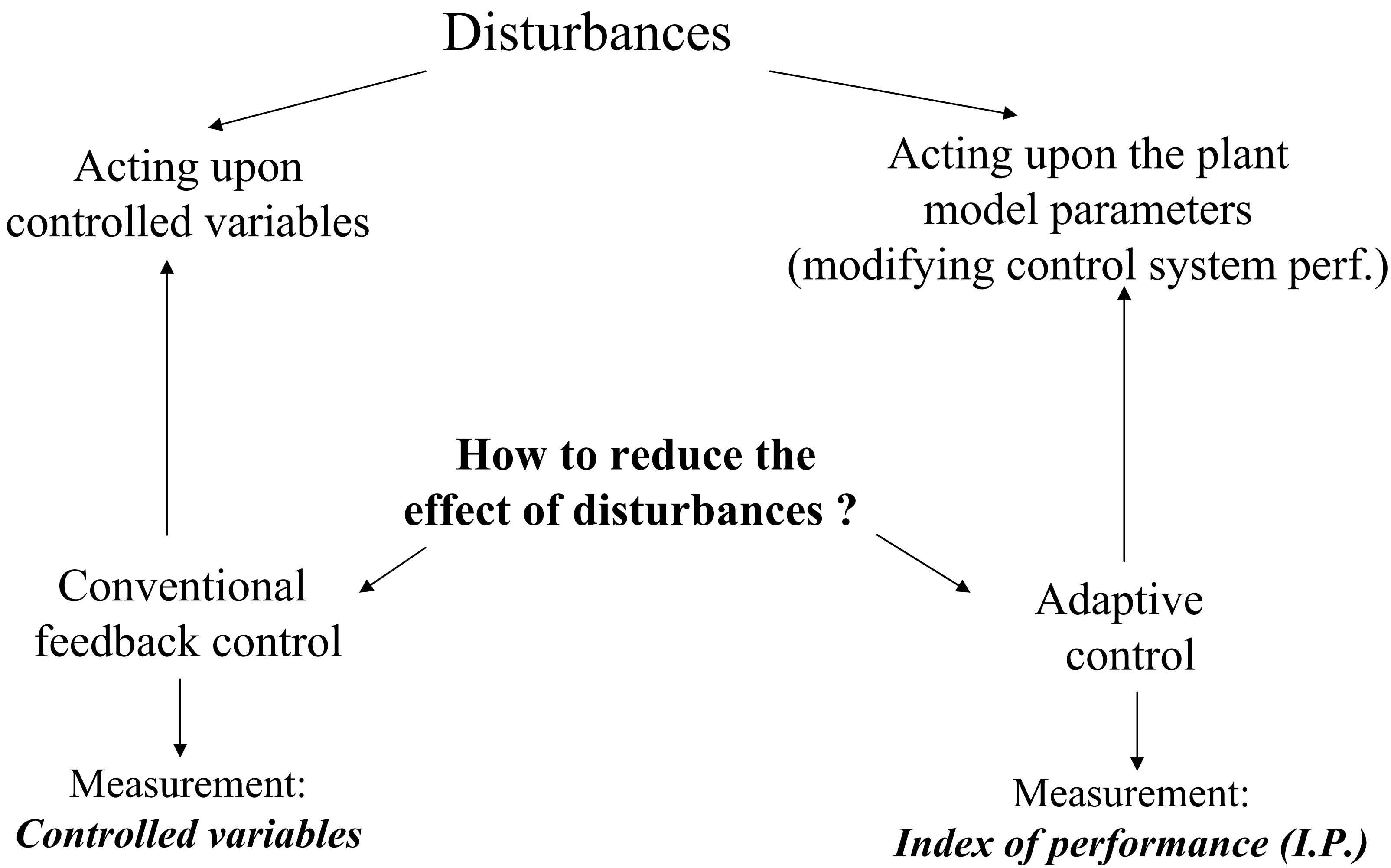
An adaptive control structure

Remark:
An adaptive control system is *nonlinear* since controller parameters will depend upon *u* and *y*

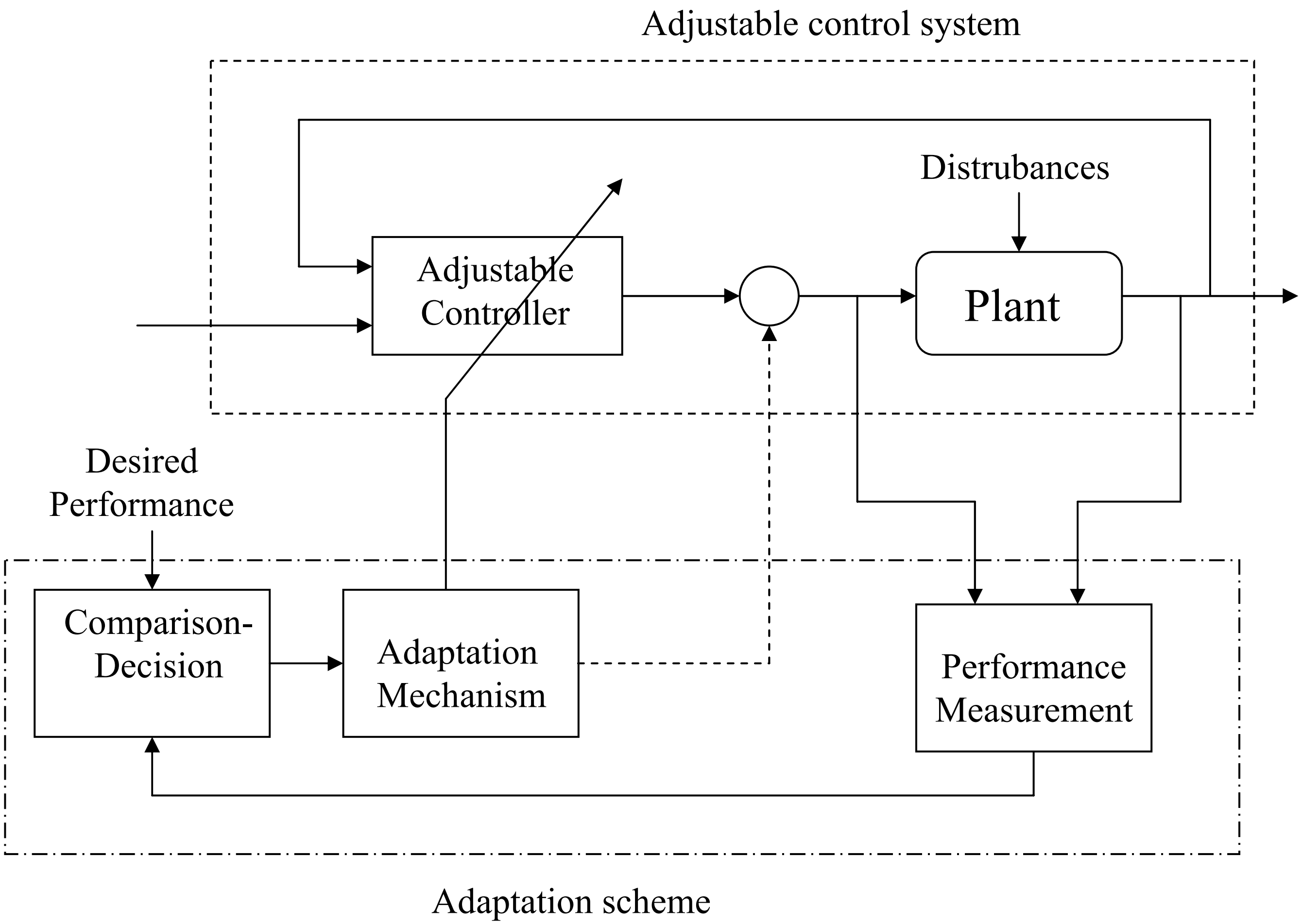
Adaptive control- Why ?

- High performance control systems may require precise tuning of the controller but plant (disturbance) model parameters may be unknown or time-varying
- "Adaptive Control" techniques provide a systematic approach for automatic on-line tuning of controller parameters
- "Adaptive Control" techniques can be viewed as approximations of some nonlinear stochastic control problems (not solvable in practice)
- Objective of "Adaptive Control" : *to achieve and to maintain acceptable level of performance when plant (disturbance) model parameters are unknown or vary*

Adaptive Control versus Conventional Feedback Control



Adaptive Control – Basic Configuration



Adaptive Control versus Conventional Feedback Control

Conventional Feedback Control System	Adaptive Control System
Obj.: Monitoring of the “controlled” variables according to a certain IP for the case of known parameters	Obj.: Monitoring of the performance (IP) of the control system for unknown and varying parameters
Meas.: Controlled variables	Meas.: Index of performance (IP)
Transducer	IP measurement
Reference input	Desired IP
Comparison block	Comparison decision block
Controller	Adaptation mechanism

Adaptive Control versus Conventional Feedback Control

A conventional feedback control system is mainly dedicated to the *elimination of the effect of disturbances* upon the controlled variables.

An adaptive control system is mainly dedicated to the *elimination of the effect of parameter disturbances (variations)* upon the performance of the control system.

Adaptive control system = hierarchical system:

- **Level 1 : Conventional feedback system**
- **Level 2 : Adaptation loop**

Fundamental Hypothesis in Adaptive Control

For any possible values of plant (disturbance) model parameters there is a controller with a fixed structure and complexity such that the specified performances can be achieved with appropriate values of the controller parameters

The task of the adaptation loop is solely to search for the "good" values of the controller parameters

Adaptive Control versus Robust Control

Adaptive control can further improve the performance of a robust control system by:

- expanding the range of uncertainty for which performance specification can be achieved
- better tuning of the nominal controller

For building an adaptive control systems robustness issues for the underlying controller design can not be ignored.

The objective is to add adaptation capabilities to a robust controller and not to use adaptive approach for tuning a non robust controller.

Conventional Control – Adaptive Control - Robust Control

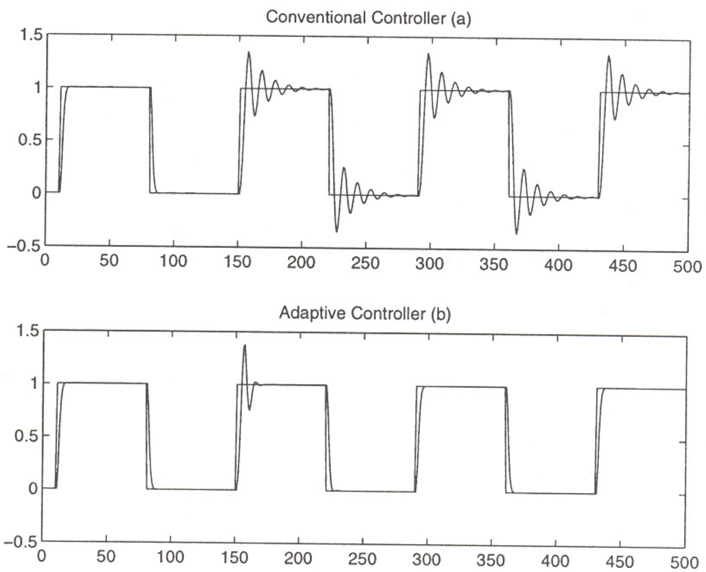


Figure 1.2.2: *Comparison of an adaptive controller with a conventional controller (fixed parameters), a) Fixed parameters controller, b) Adaptive controller*

Conventional versus Adaptive

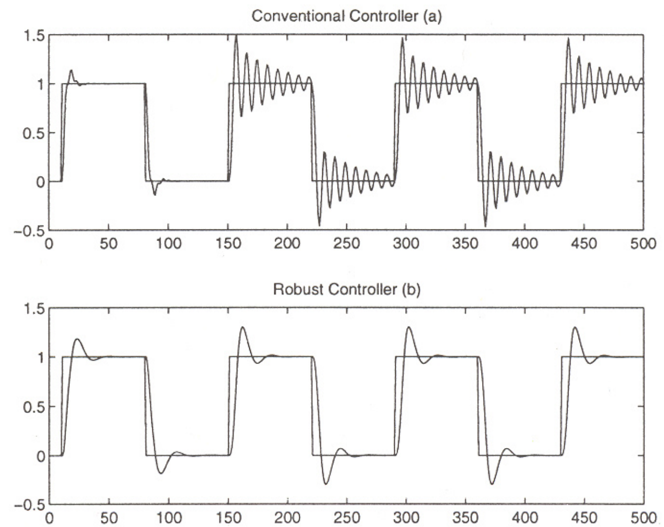


Figure 1.2.4: *Comparison of conventional feedback control and robust control, a) conventional design for the nominal model, b) robust control design*

Conventional versus Robust

Conventional Control – Adaptive Control - Robust Control

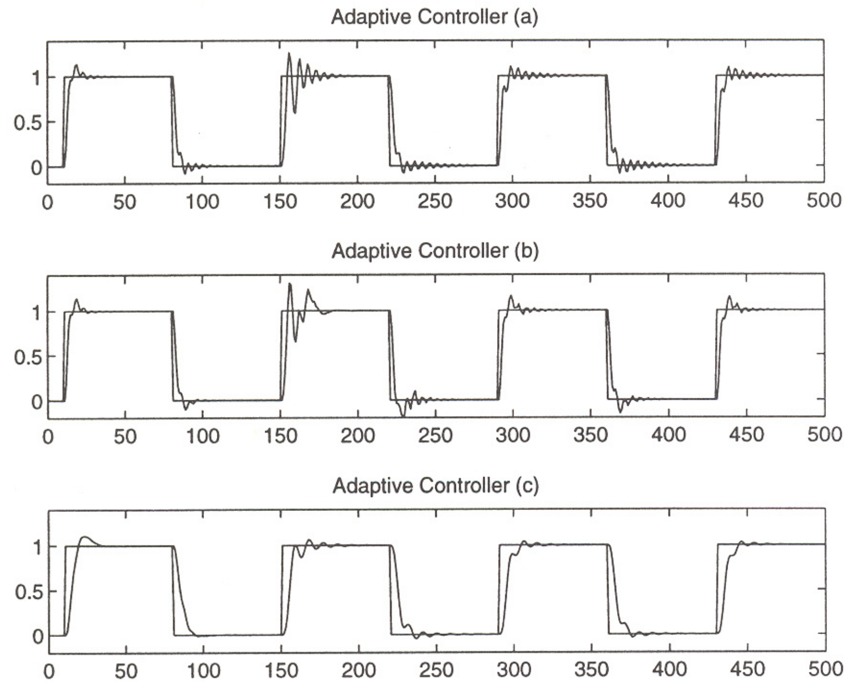


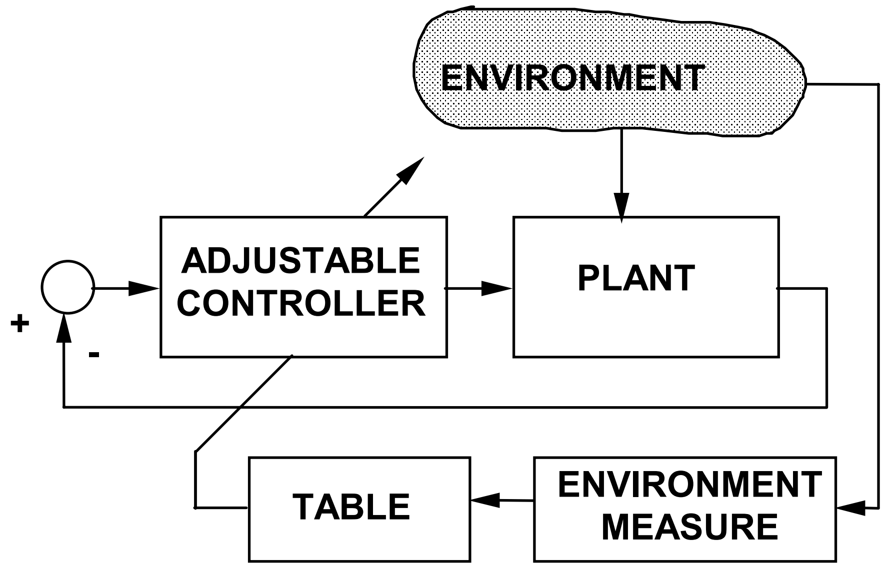
Figure 1.2.5: *Comparison of adaptive controller, a) adaptation added to the conventional controller (Fig. 1.2.4.a), b) robust adaptation added to the conventional controller (Fig. 1.2.4.a), c) adaptation added to the robust controller (Fig. 1.2.4.b)*

Robust Adaptive Control and *Adaptive Robust Control* are different.

What we need : Robust Adaptation of a Robust Controller

Basic Adaptive Control Configurations

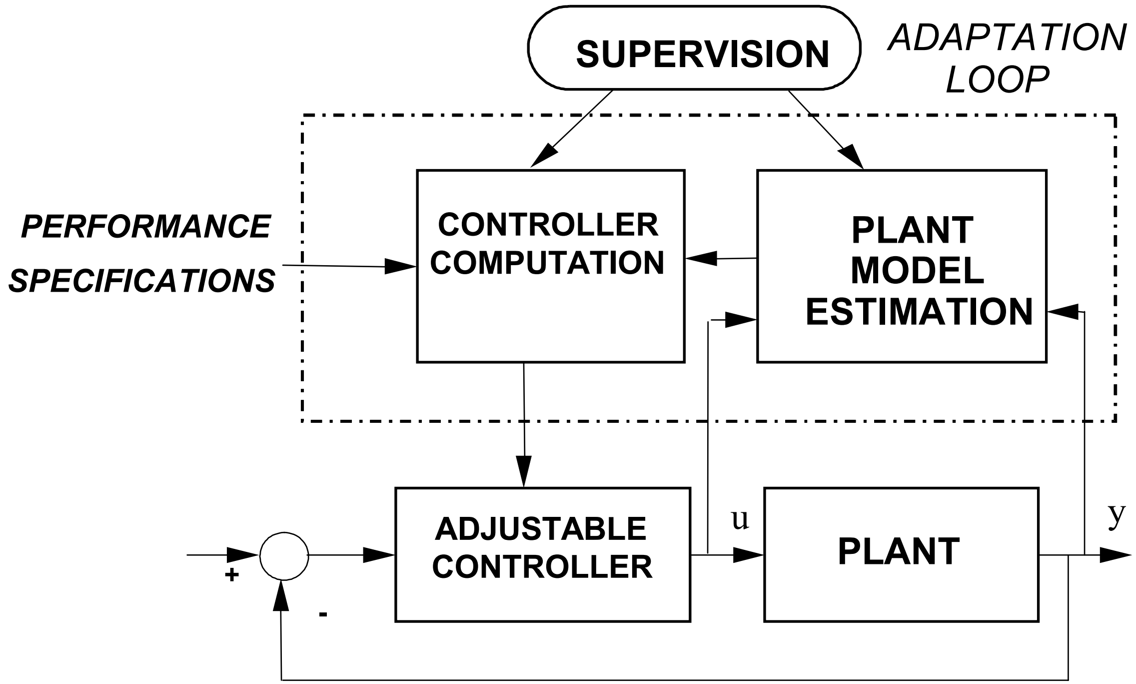
Open Loop Adaptive Control



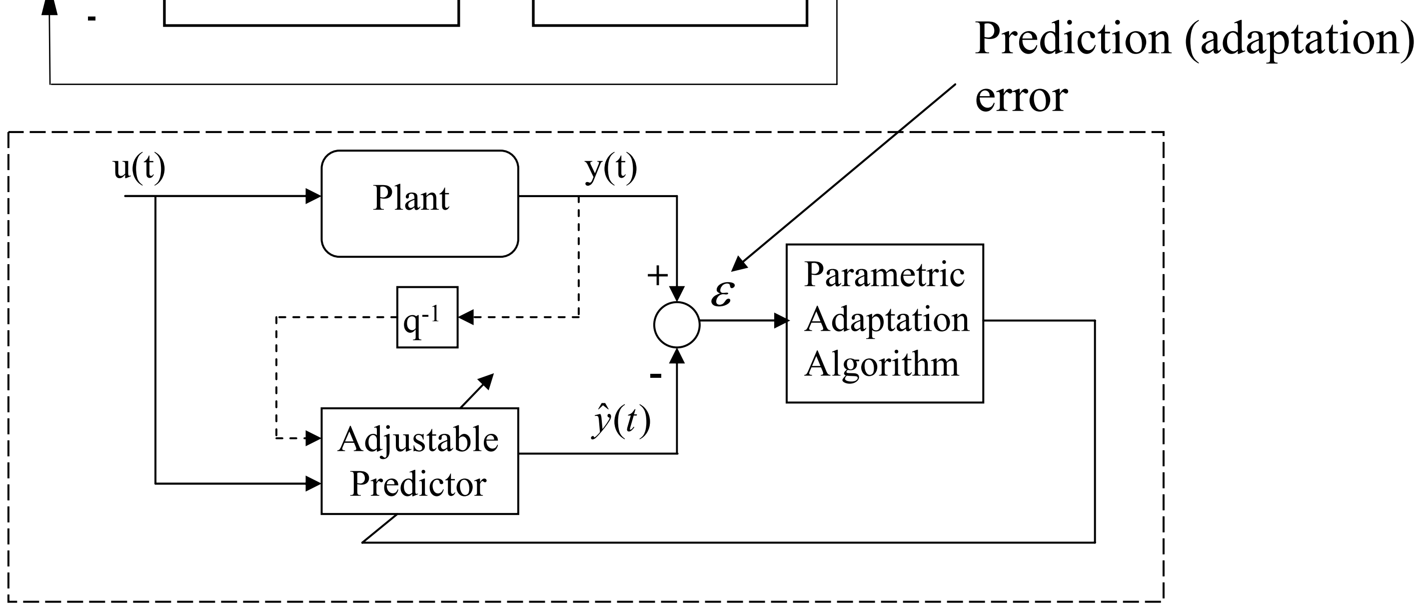
***Assumption*: known and rigid relationship between some measurable variables (characterizing the environment) and the plant model parameters

Called also: gain-scheduling systems

Indirect Adaptive Control

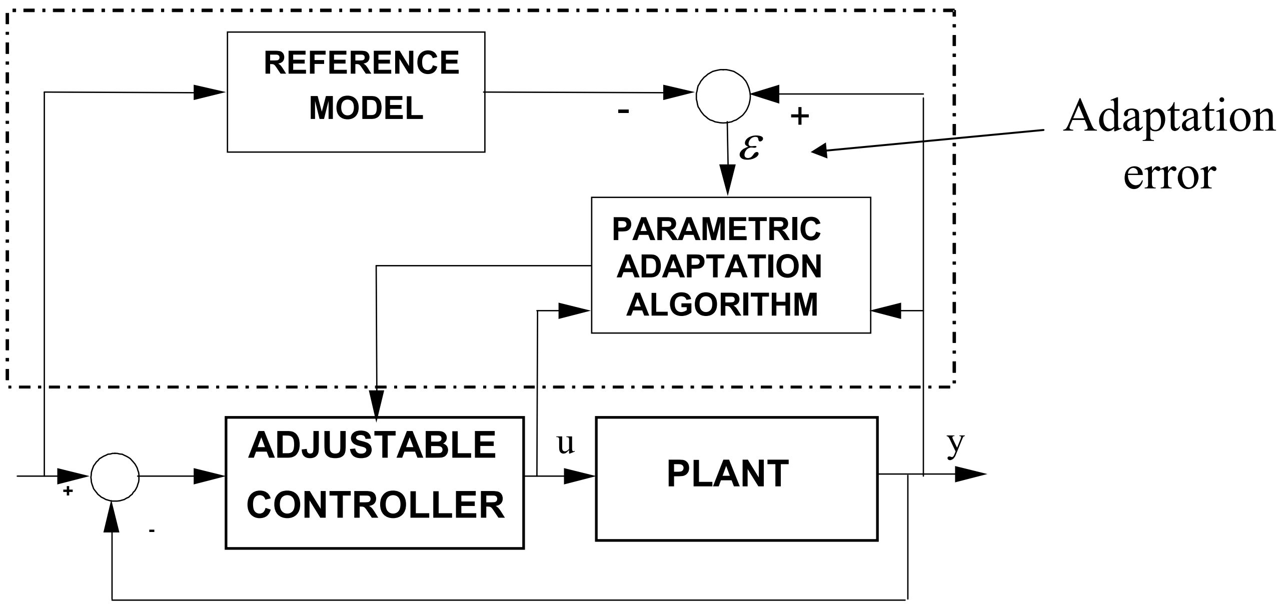


Plant Model Basic Estimation Scheme



Direct Adaptive Control
(model reference adaptive control)

The reference model gives the desired time trajectory of the plant output



Resemblance with plant parameter estimation scheme

Reference model ⟷ Plant

Adjustable feedback syst. ⟷ Adjustable predictor

Parametric adaptation algorithm (PAA)

Parameter vector θ = contains all the parameters of the model (or of the controller)

$$\begin{bmatrix}\text{New parameters}\\ \text{estimation}\\ \text{(vector)}\end{bmatrix} = \begin{bmatrix}\text{Old parameters}\\ \text{estimation}\\ \text{(vector)}\end{bmatrix} +$$

$$\begin{bmatrix}\text{Adaptation}\\ \text{Gain}\\ \text{(matrix)}\end{bmatrix} \times \begin{bmatrix}\text{Measurement}\\ \text{function}\\ \text{(vector)}\end{bmatrix} \times \begin{bmatrix}\text{Error prediction}\\ \text{function}\\ \text{(scalar)}\end{bmatrix}$$

Regressor vector

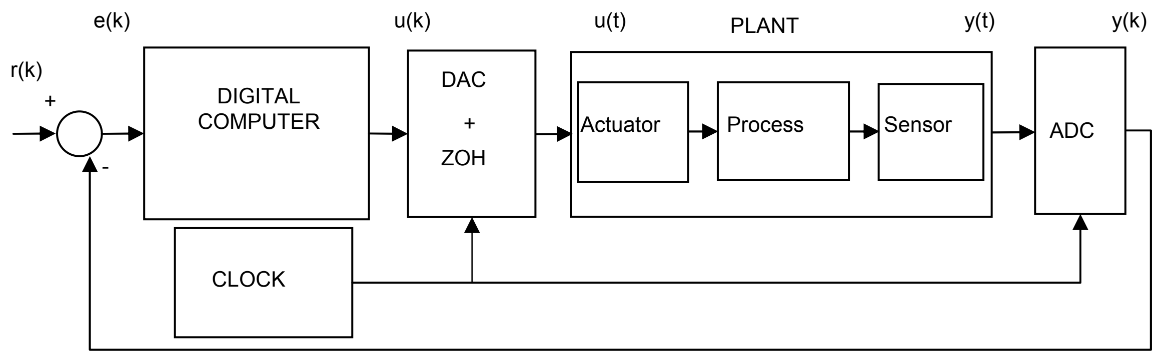
Estimated Parameter vector

$$\boxed{\hat{\theta}(t+1) = \hat{\theta}(t) + F\Phi(t)\nu(t+1)}$$

$(\nu = f(\varepsilon))$

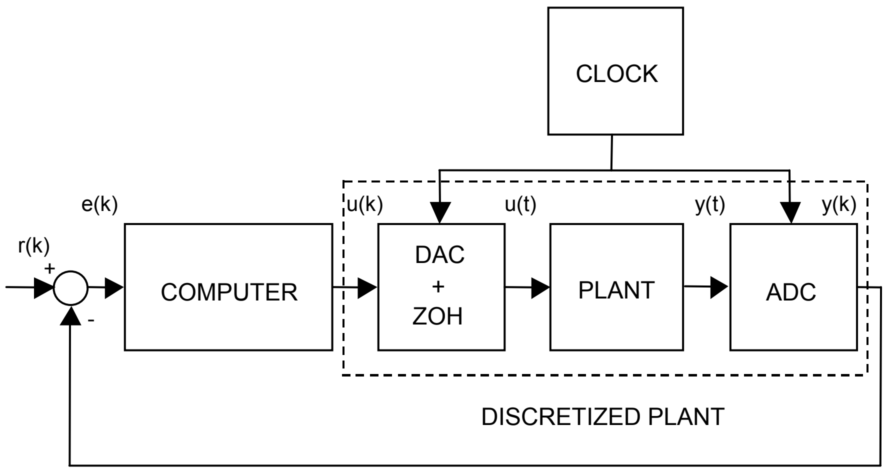
Digital Control System

The *control law* is implemented on a digital computer



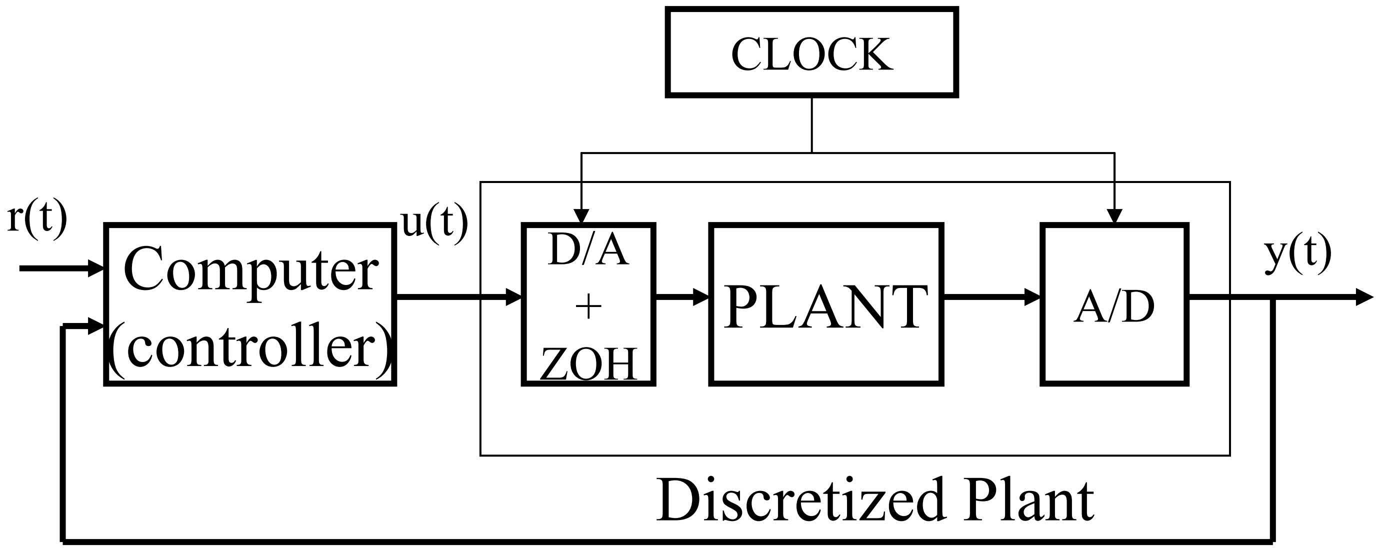
ADC: analog to digital converter
DAC: digital to analog converter
ZOH: zero order hold

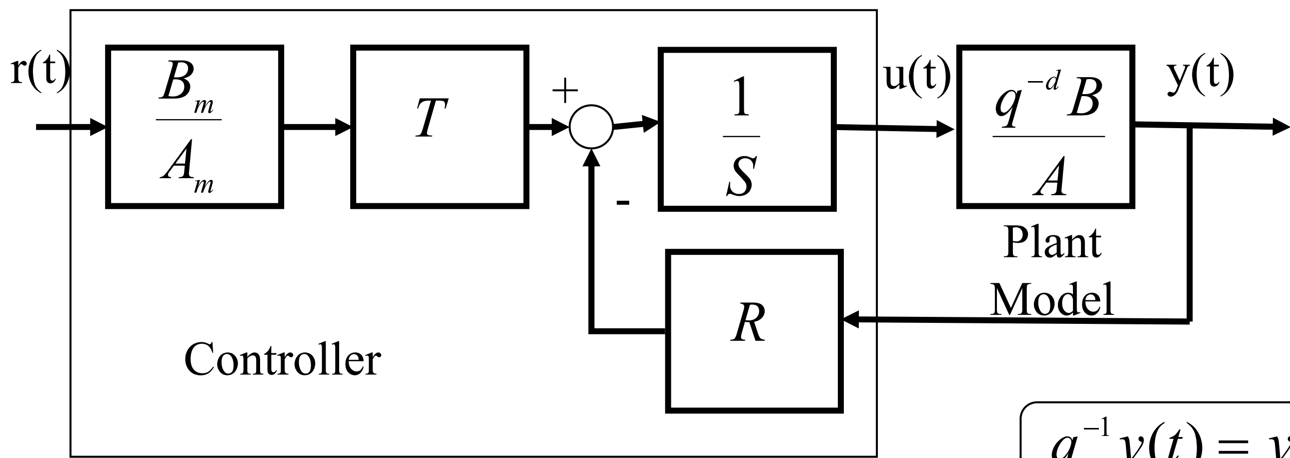
Digital Control System



- Sampling time depends on the system bandwidth
- Efficient use of computer resources

The R-S-T Digital Controller





$$q^{-1}y(t) = y(t-1)$$

How to get a Direct Adaptive Control scheme ?

- Express the performance error in term of difference between the parameters of an unknown optimal controller and those of the adjustable controller

- Re-parametrize indirect adaptive control scheme (if possible) such that the adaptive predictor will provide directly the estimated parameters of the controller.

See : Adaptive Control (Landau, Lozano, M'Saad) pg 19

The number of situation for which a direct adaptive control scheme can be developed is limited.

Adaptive Control Schemes. Regimes of operation

- **Adaptive regime**

1. Controller parameters are updated at every sampling time
2. Plant parameters are estimated at every sampling time but controller parameters are updated only every N samples (N small)
3 Adaptation works only when there is enough excitation

- **Self-tuning regime** (parameters are supposed unknown but constant)

1 Parameter adaptation algorithms with decreasing adaptation gain
2 Controller parameters are either updated at every sampling time or kept constant during parameter estimation
3 An external excitation is applied during tuning or plant identification

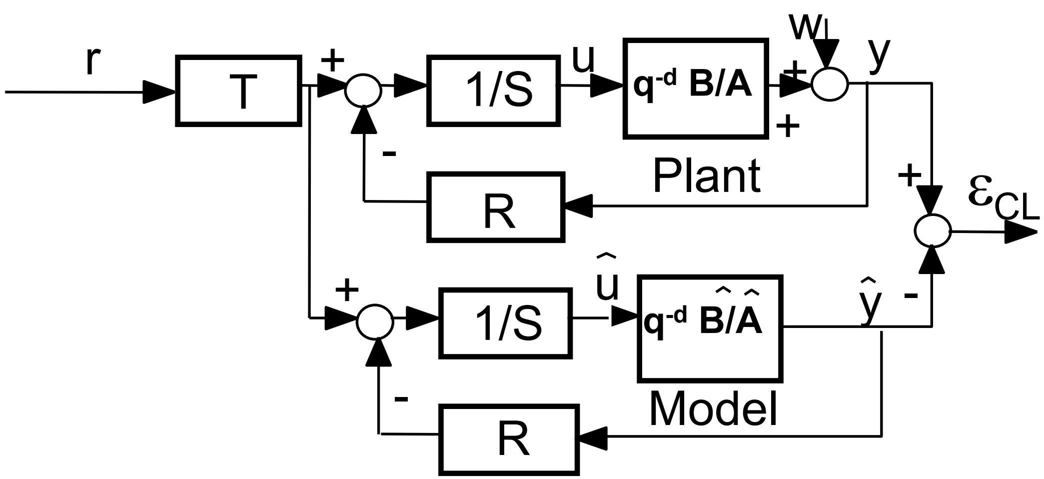
Remark

If controller parameters are kept constant during parameter estimation this is called "auto-tuning". For the indirect approach this corresponds to "plant identification in closed loop operation and controller redesign"

Identification in Closed Loop and Adaptive Control

- Identification in closed loop operation using appropriate algorithms provides better models for design
- An iterative approach combining identification in closed loop followed by a re-design of the controller is a very powerful (auto-)tuning scheme

Iterative Identification in Closed Loop and Controller Re-Design



Step 1 : Identification in Closed Loop

-Keep controller constant

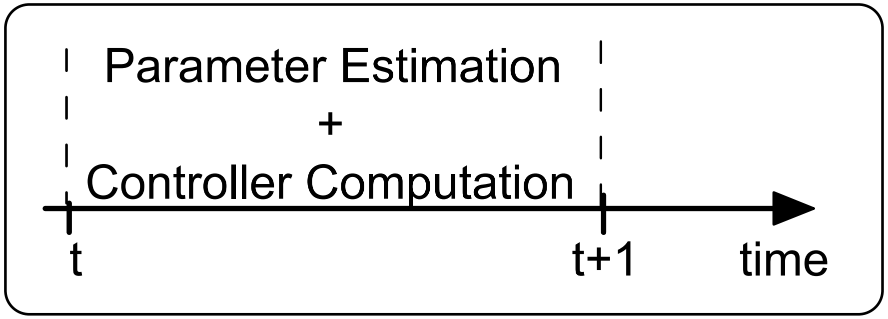
-Identify a new model such that ε_{CL} ↘

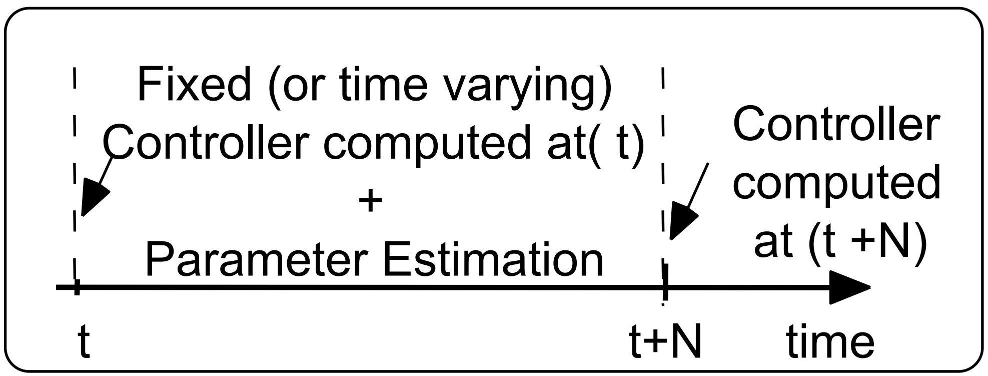
Step 2 : Controller Re – Design

- Compute a new controller such that ε_{CL} ↘

Repeat 1, 2, 1, 2, 1, 2,…

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 and Adaptive Regulation

Adaptive Control

Plant model is unknown and time varying
The disturbance model is known and constant

Adaptive Regulation

Plant model is known and constant
The disturbance model is unknown and time varying

Adaptive control and regulation

Very difficult problem since is extremely hard to distinguish in the performance (prediction) error what comes from plant model error and what comes from disturbance model error

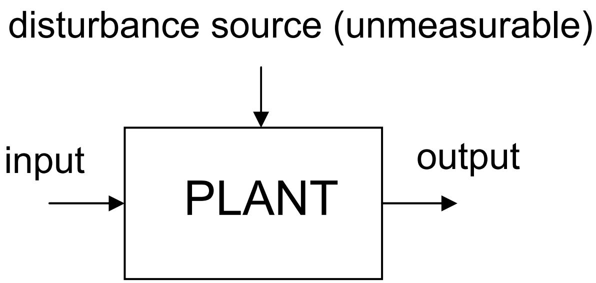
Rem:

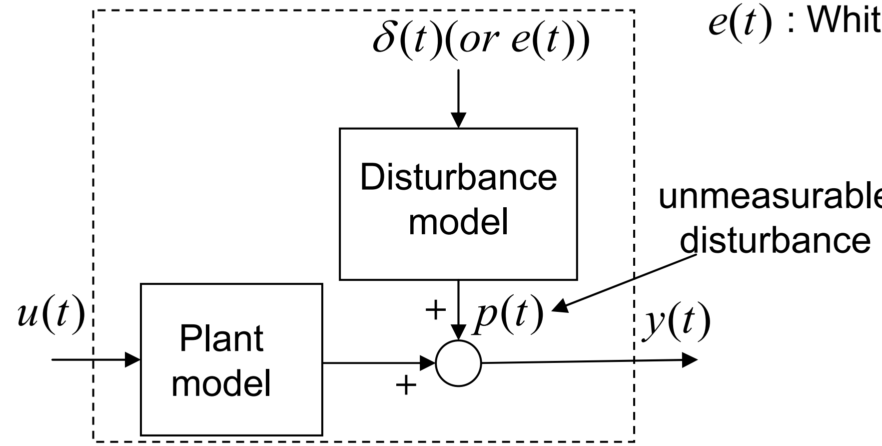
The "internal model principle" has to be used in all the cases

Adaptive Control

$\delta(t)$: Dirac

$e(t)$: White noise



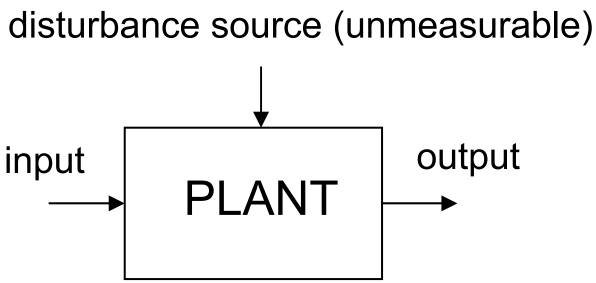


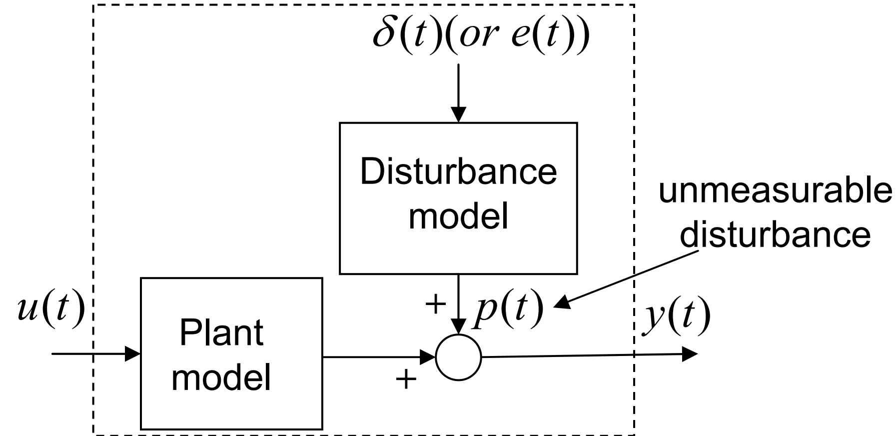
Objective : tracking/disturbance attenuation performance

- **Focus on adaptation with respect to plant model parameters variations**
- The model of the disturbance is assumed to be known and constant
- Only a level of attenuation in a frequency band is required*
- **No effort is made to simultaneously estimate the model of the disturbance**

*) Except for known DC disturbances (use of integrators)

Adaptive Regulation





Objective : Suppressing the effect of the (unknown) disturbance*

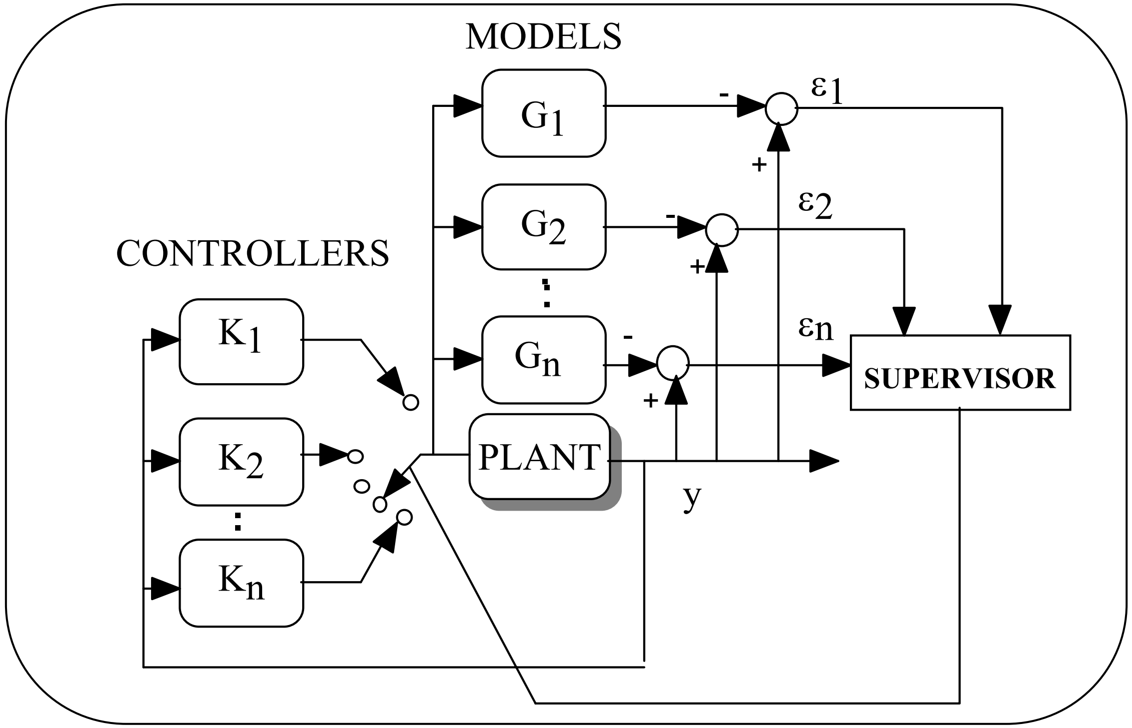
- **Focus on adaptation with respect to disturbance model parameters variations**
- Plant model is assumed to be known (a priori system identification) and almost constant
- Small plant parameters variations handled by a robust control design
- **No effort is made to simultaneously estimate the plant model**

*) Assumed to be characterized by a rational power spectrum if stationary

Use of a priori information for improving adaptation transients

- Before using an adaptive control scheme, an analysis of the system is done and this is followed by plant identification in various regimes of operation
- The availability of models for various regimes of operation allows to design robust controllers which can assure satisfactory performance in a region of the parameter space around each of the identified models.
- Provided that we can detect in what region the system is, the appropriate controller can be used
- "Indirect adaptive control" can not detect enough fast the region of operation but can make a "fine" tuning over a certain time.
- In case of rapid parameter changes the adaptation transients in indirect adaptive control may be unacceptable.
- There is a need to improve these transients by taking in account the available information

Supervisory Control

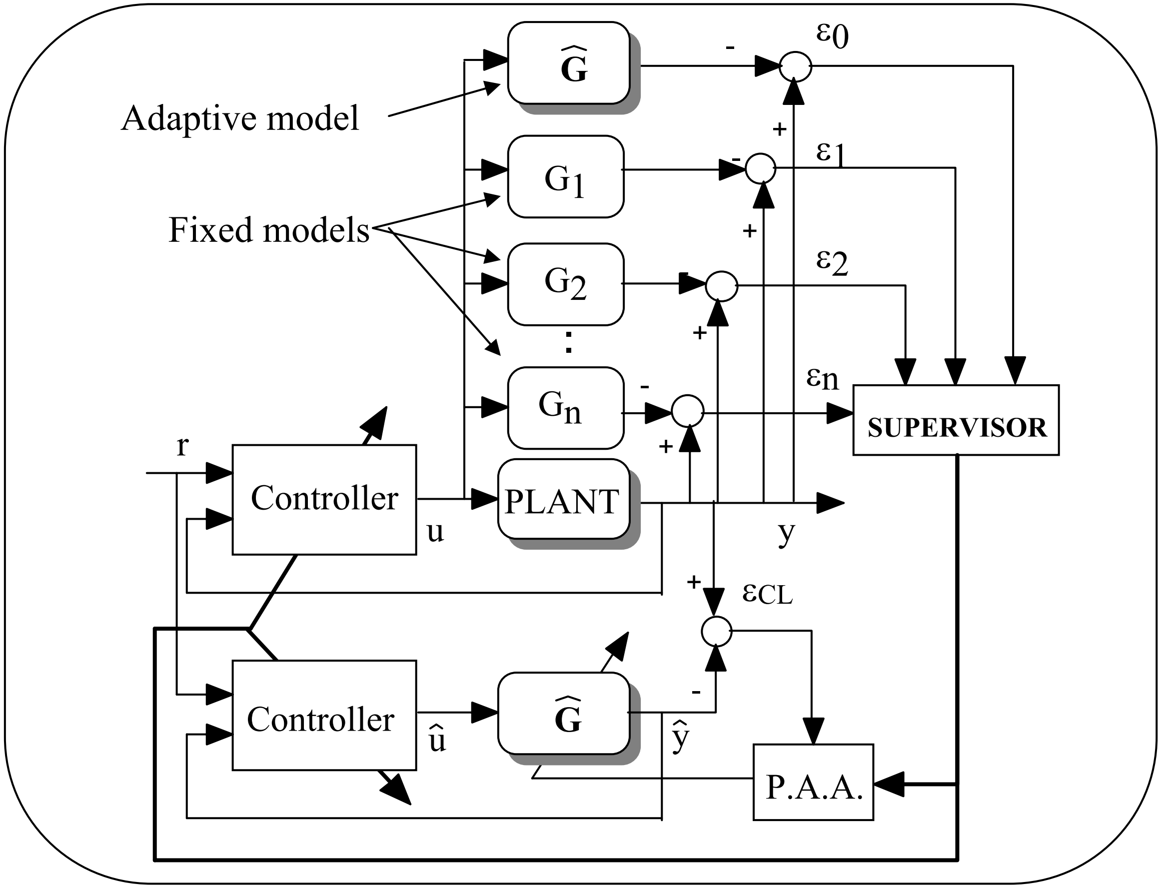


The "supervisor":

- will check what "plant-model" error is minimum
- will switch to the controller associated with the selected model

Can provide a very fast decision (if there are not too many models) but not a fine tuning

Adaptive Control with Multiple Models

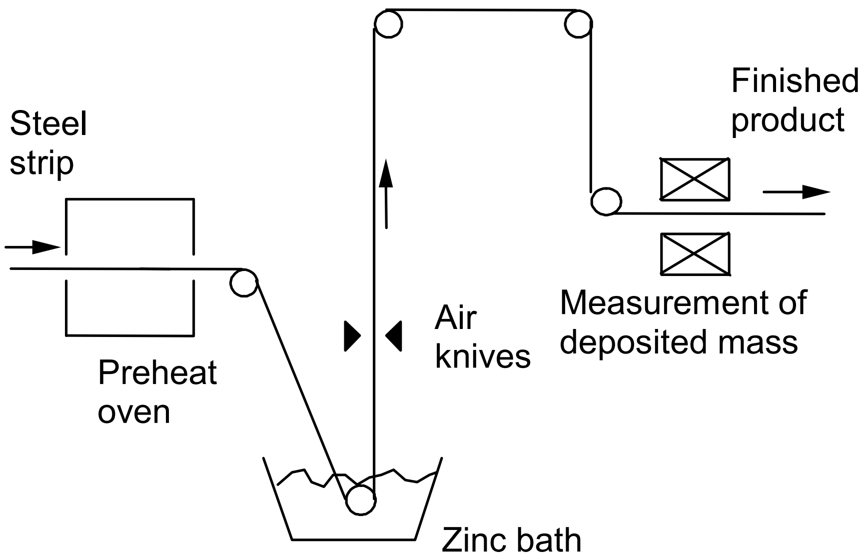


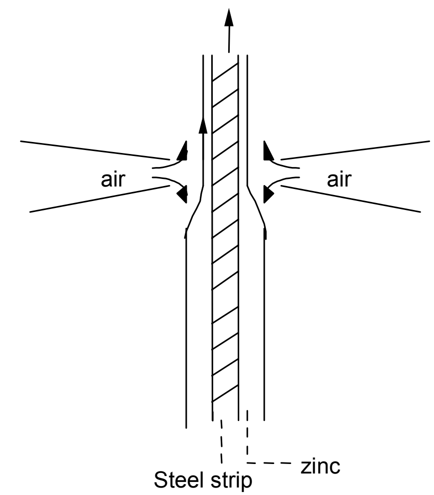
The supervisor select the best fixed model and then the adaptive model will be selected

Multiple fixed models : *improvement of the adaptation transients*
Adaptive plant model estimator (CLOE Estimator) : *performance improvement*

Some Applications of Adaptive Control

Open Loop Adaptive Control of Deposited Zinc in Hot-Dip Galvanizing





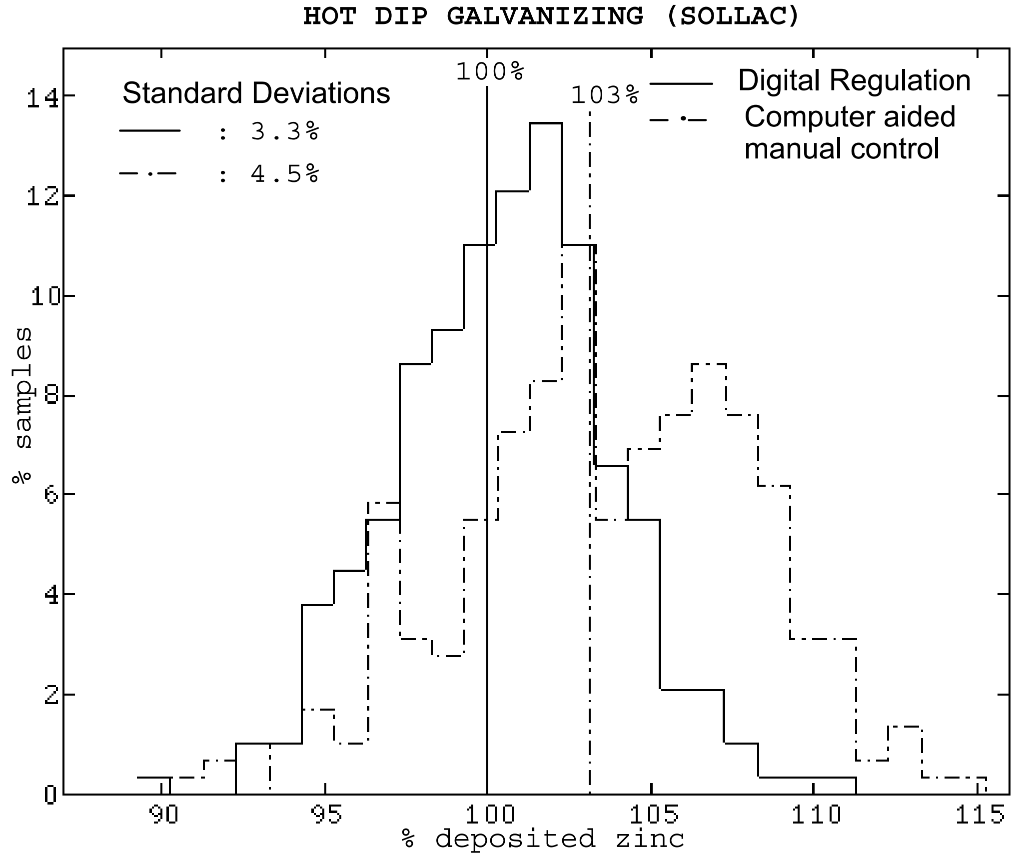
input: air knives pressure
output: measured deposited mass

$$H(s) = \frac{Ge^{-s\tau}}{1+sT} \quad ; \quad \tau = \frac{L}{V}$$

L- *distance knives –measure*
V- *strip speed*

- delay varies with the speed
- G and T depend upon strip speed and distance between knives and steel strip

Open Loop Adaptive Control of Deposited Zinc in Hot-Dip Galvanizing



Adaptation done with respect to:

- Steel strip speed
- Distance between air knives and steel strip

9 operation regions

The sampling period is tied to the strip speed to have constant discrete time delay

Direct Adaptive Control of a Phosphate Dryer Furnace

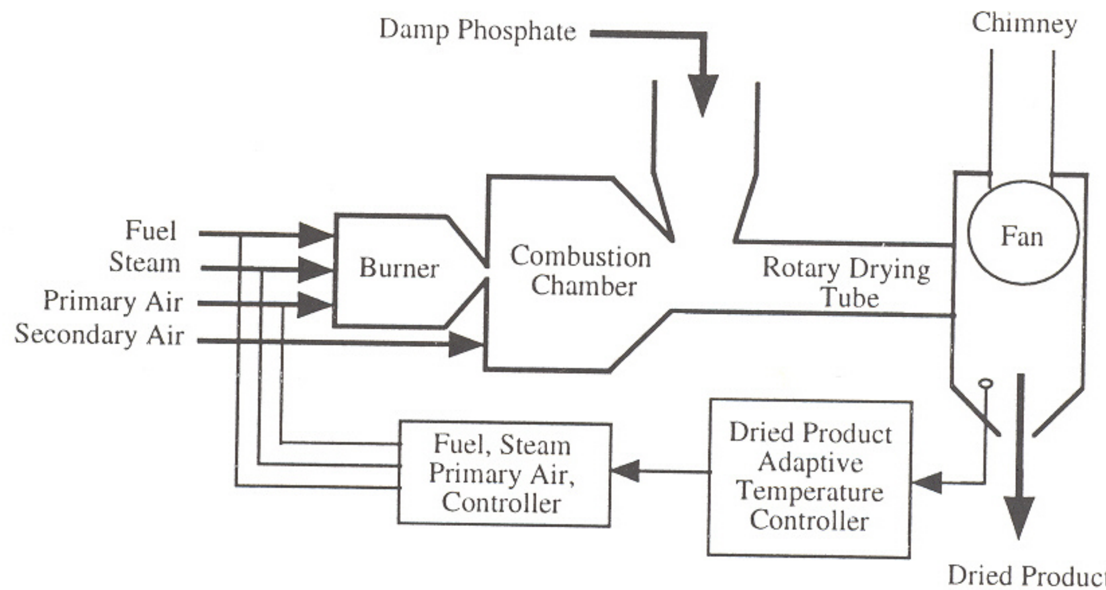


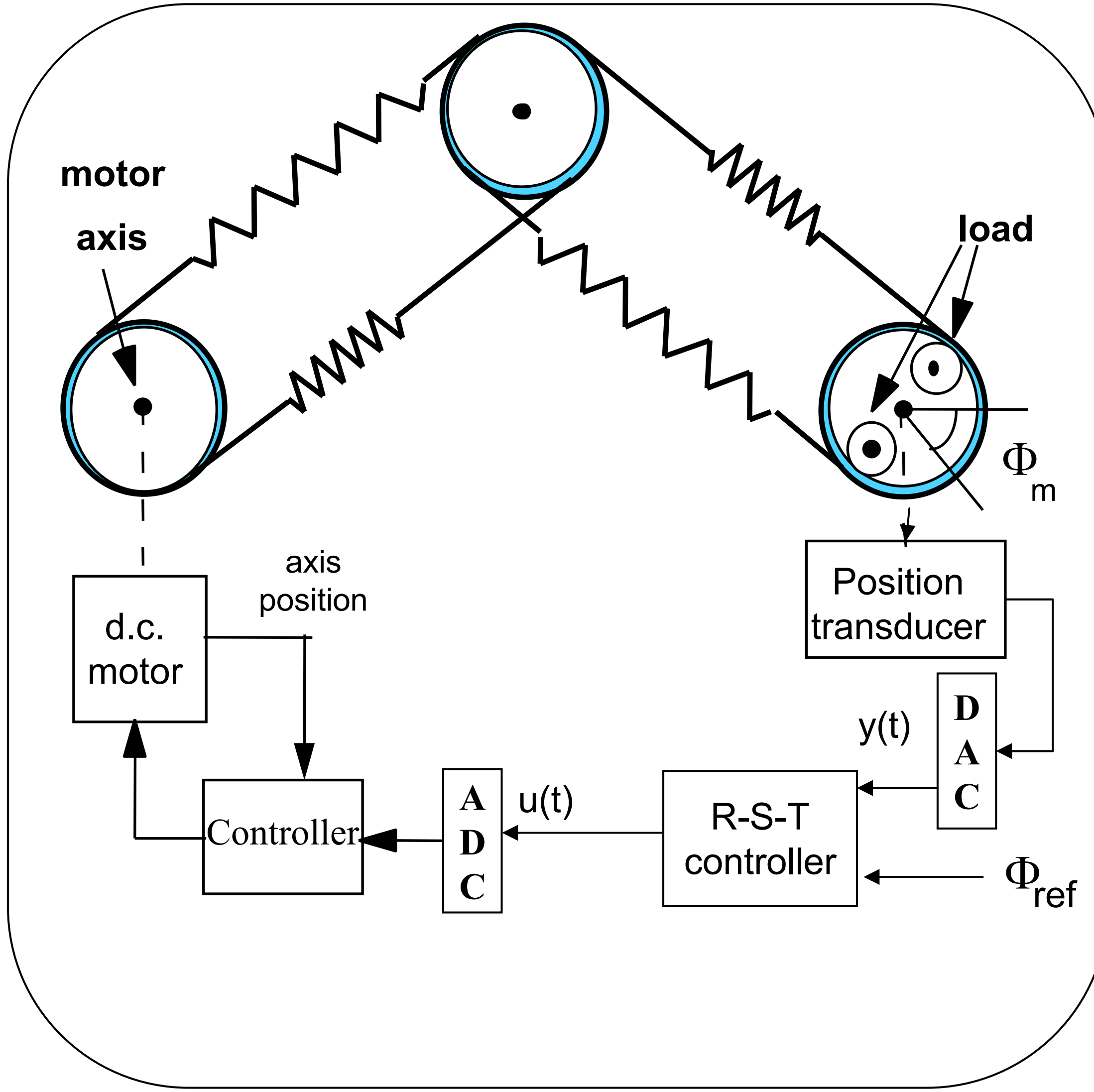
Figure 1.4.2: *Phosphate drying furnace*

Large delay : 90 s

Better quality(reduction of the humidity standard deviation)
Reduction of fuel comsumption and of the thermal stress.

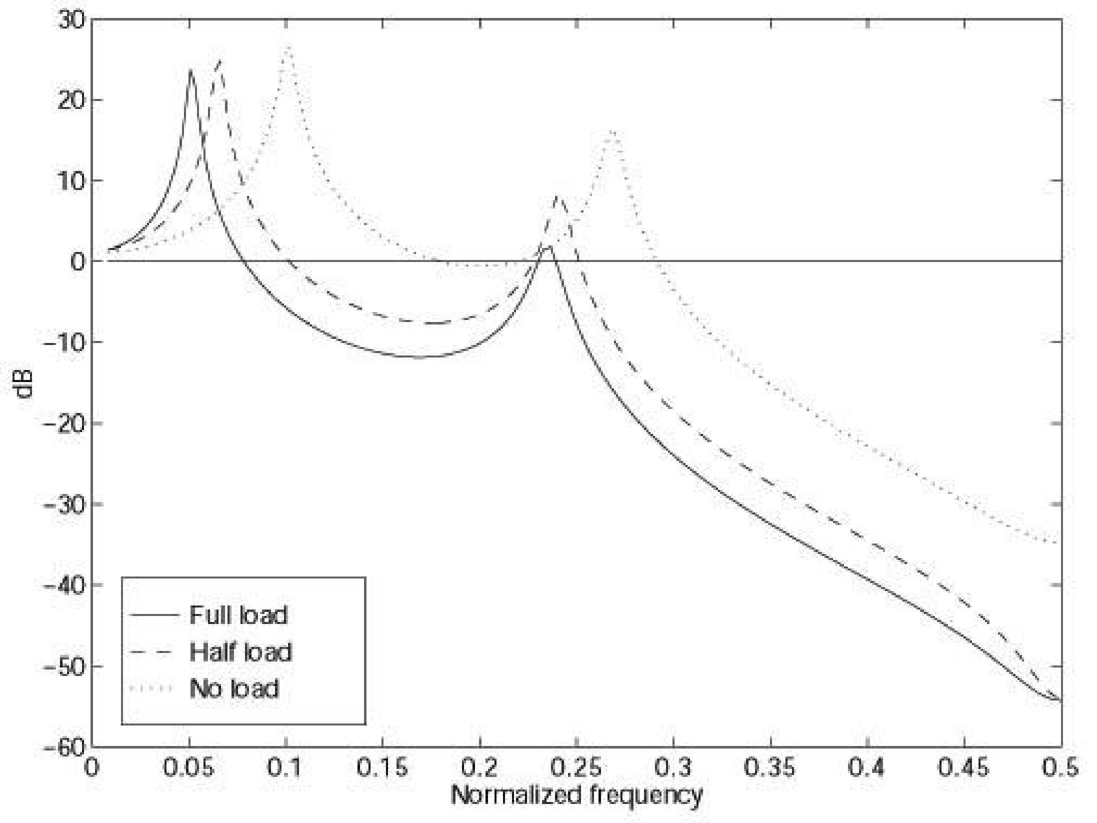
Adaptive Control of a Flexible Transmission

The flexible transmission



Adaptive Control of a Flexible Transmission

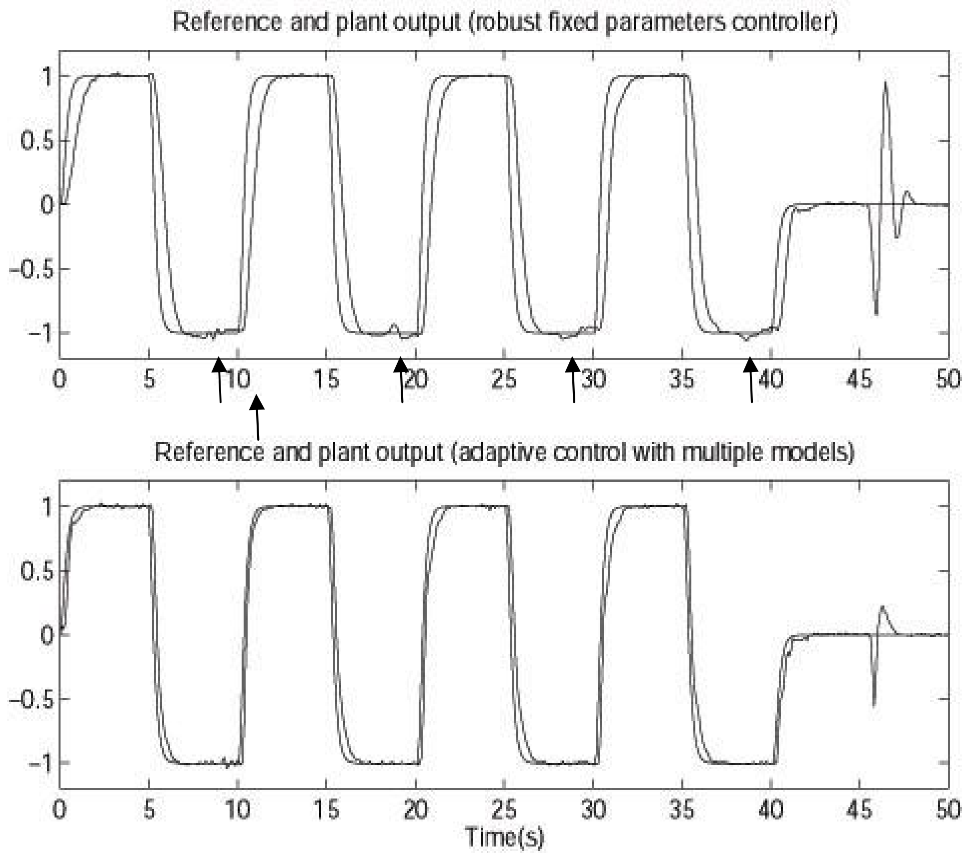
Frequency characteristics for various load



Rem.: the main vibration mode varies by 100%

Solution : Adaptive control with multiple models

Adaptive Control versus Robust Control

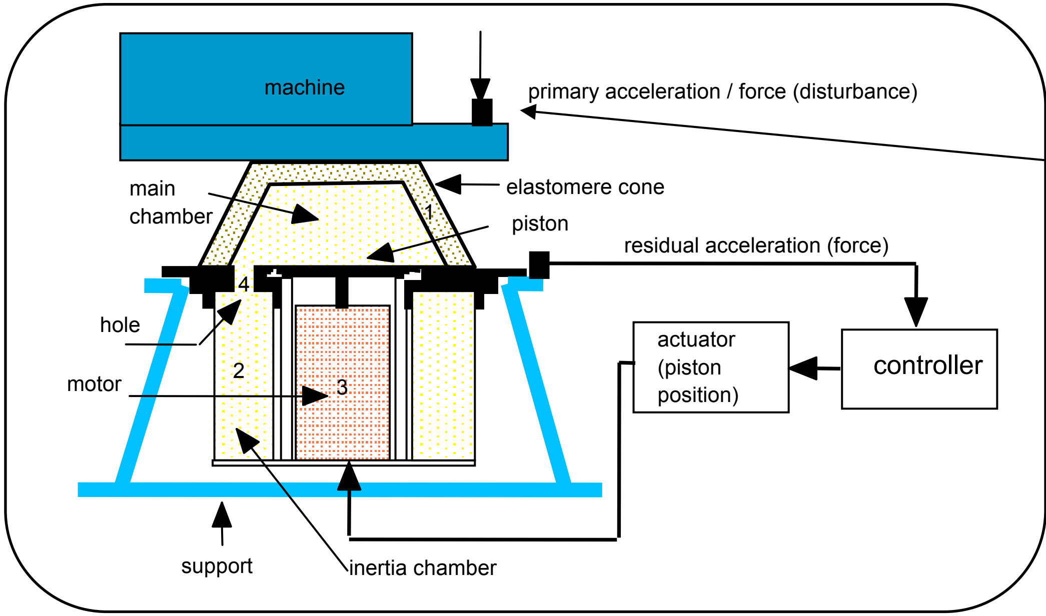


Load variations : 0% → 100% (in 4 steps, 25% each)

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

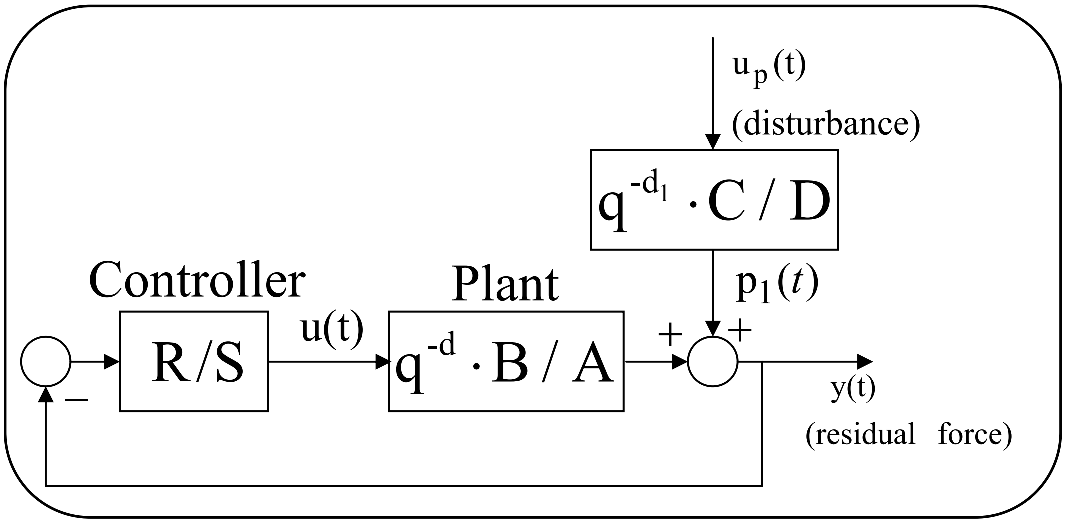
Rejection of unknown narrow band disturbances in active vibration control

The Active Suspension System



Objective:

- **Reject the effect of unknown and variable narrow band disturbances**
- **Do not use an aditional measurement**

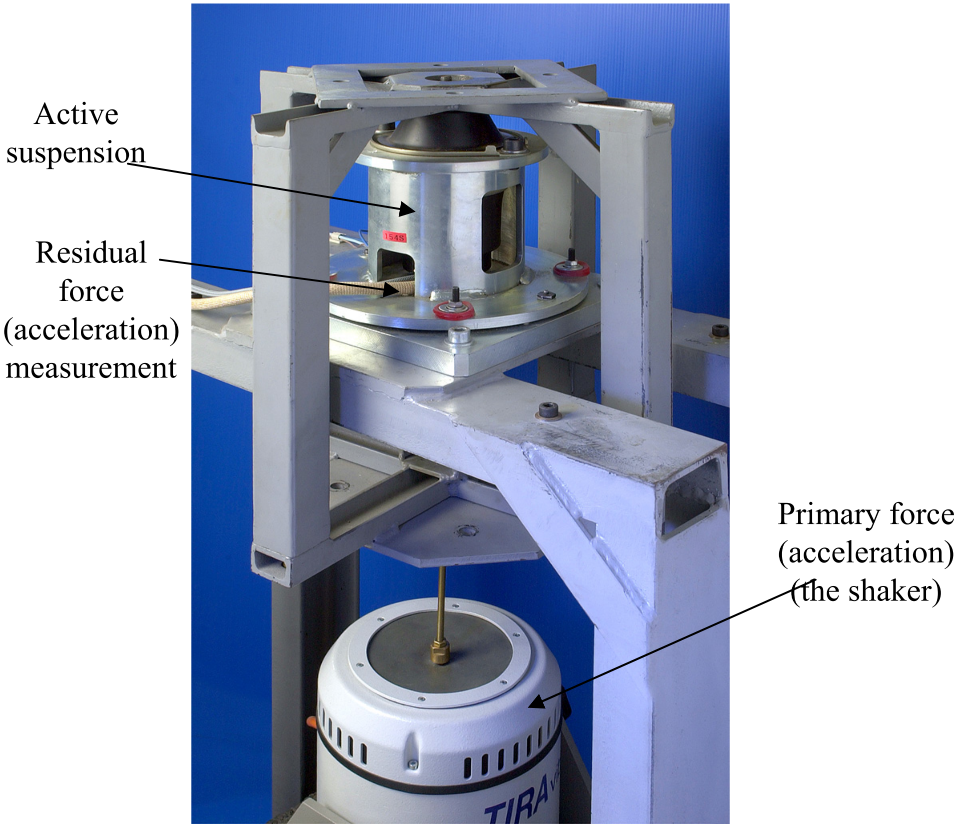


Two paths :

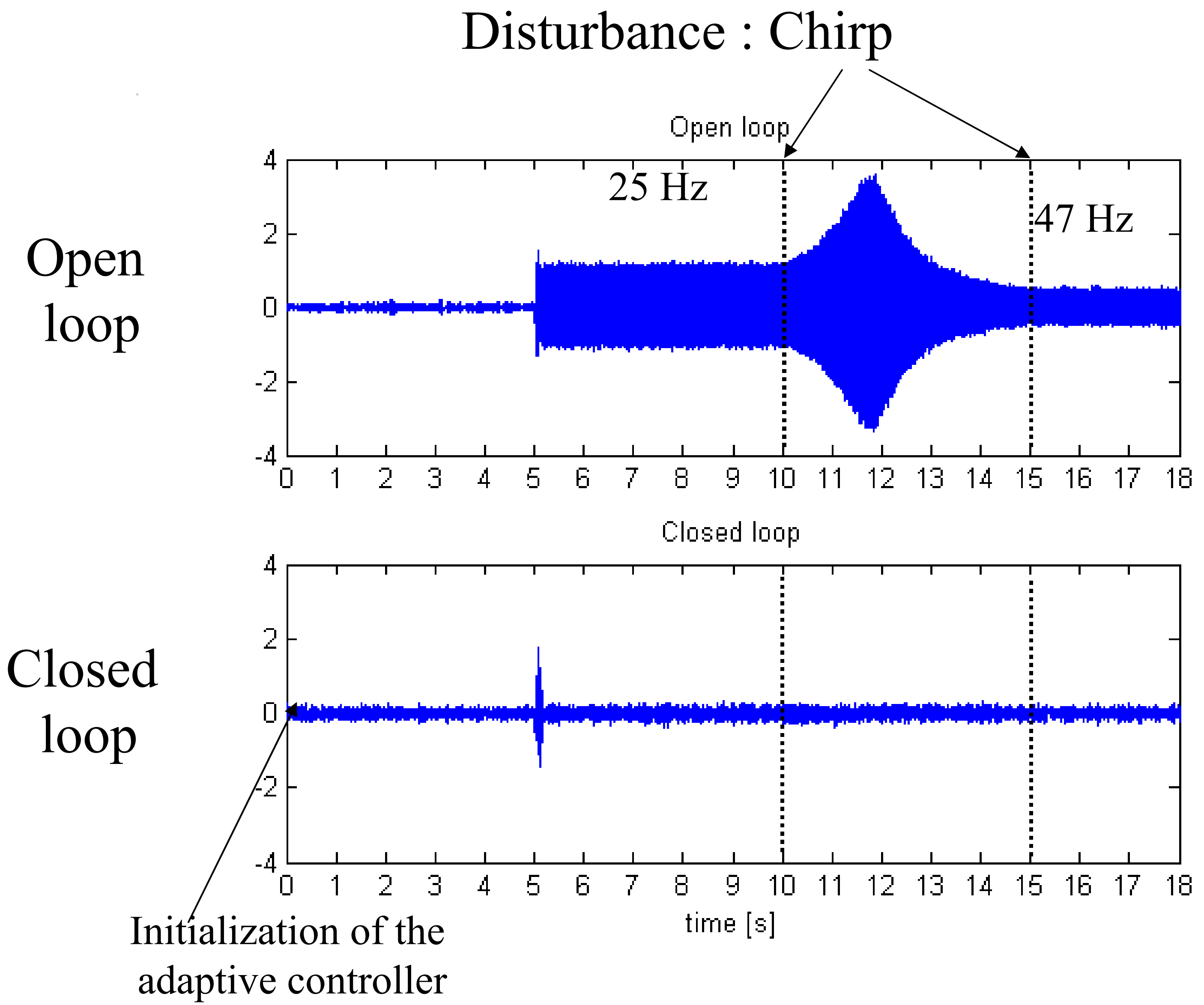
- Primary
- Secondary (double differentiator)

$$T_s = 1.25\ \text{ms}$$

The Active Suspension



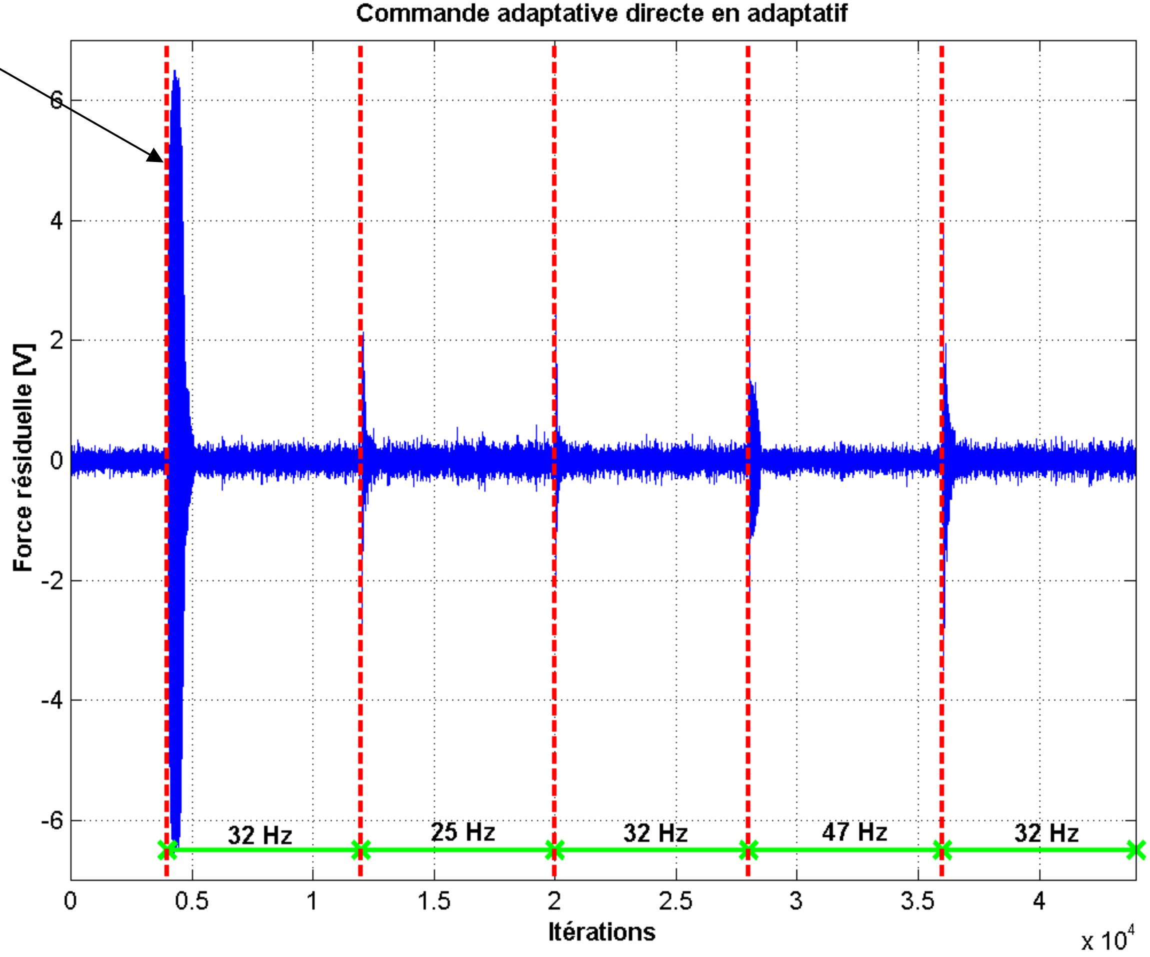
Direct Adaptive Regulation : disturbance rejection



Direct Adaptive Regulation : rejection of sinusoidal disturbances

Simultaneous controller initialization and disturbance application

Direct adaptive control



Step changes in the frequency of the disturbance