IDENTIFICATION IN CLOSED LOOP
A powerful design tool
(theory, algorithms, applications)

better models, simpler controllers

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Part 1: Introduction

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Sevilla
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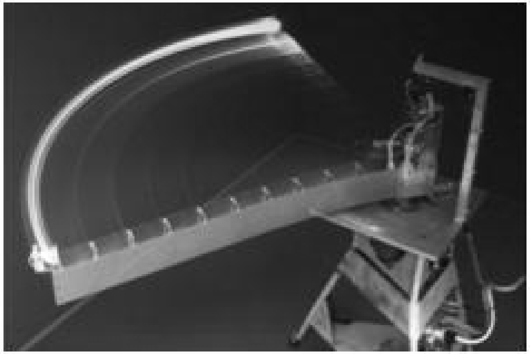
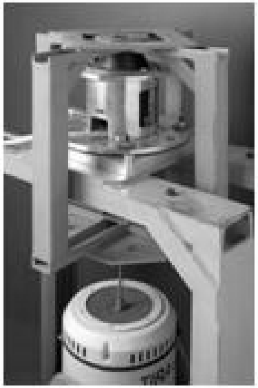
Peugeot (PSA)

Double Twist Machine (Pourtier)

Sollac (Florange) Hot Dip Galvanizing



360° Flexible Arm (LAG)



Active Suspension (Hutchinson)

Flexible transmission (LAG)

Outline

Part 1

- Introduction to identification in closed loop

Part 2

- Review of robust digital control

Part 3

- Review of open loop identification

Part 4

Identification in closed loop. Algorithms and applications

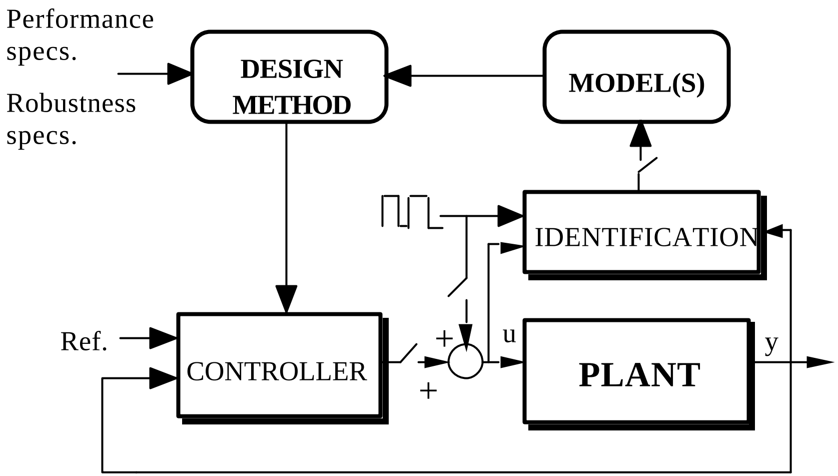
Part 5

- Direct controller reduction by identification in closed loop
- Coherence between identification in CL and controller reduction
- Concluding remarks

Outline – Part 1

- Introduction to identification in closed loop
- An example (flexible transmission)
- Objectives of identification in closed loop
- Controller reduction using identification in closed loop
- An example (an active suspension)

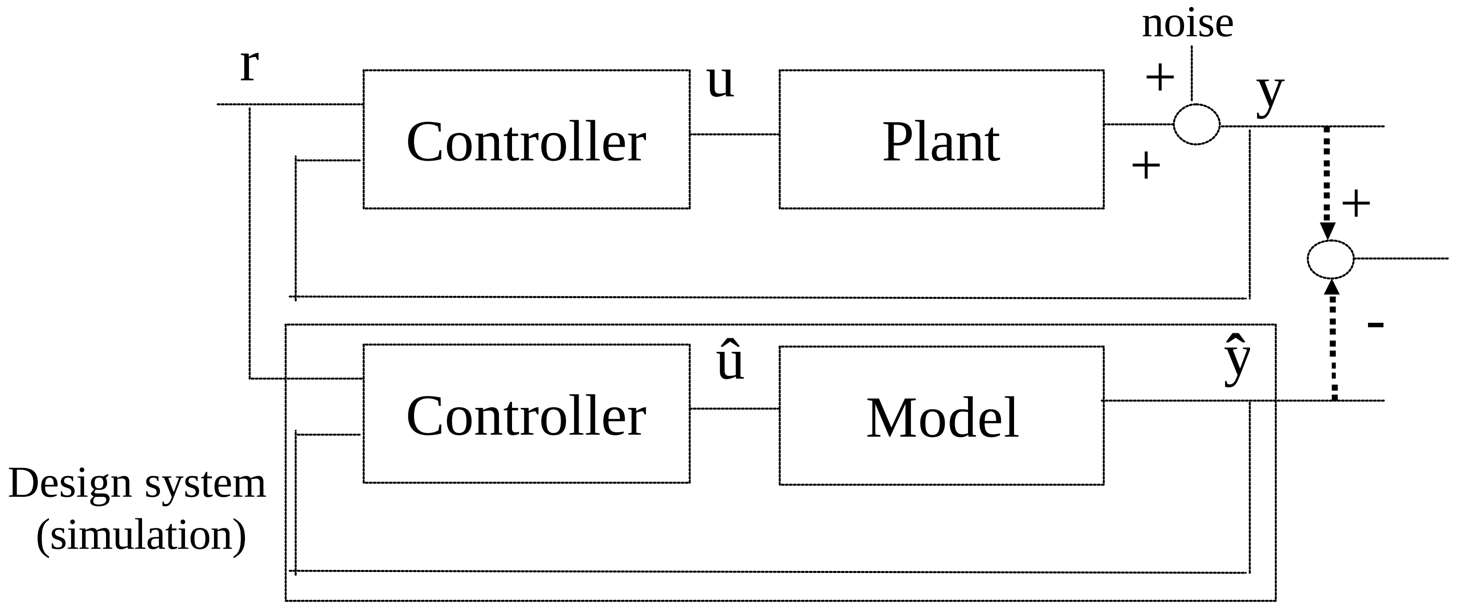
Controller Design and Validation



1) Identification of the dynamic model
2) Performance and robustness specifications
3) Compatible controller design method
4) Controller implementation
5) Real-time controller validation
(and on site re-tuning)
6) Controller maintenance (same as 5)

(5) and (6) require
identification in closed-loop

Real-Time Controller Validation



Comparison of « achieved » and « desired » performances

A useful interpretation :

Check to what extent the **model** used for design allows achievement of:
- desired nominal performances
- desired robustness specs.(sensitivity functions)

Real-Time Controller Validation

If the results are not satisfactory:

Plant model identification in *closed loop*

\+

Controller redesign

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

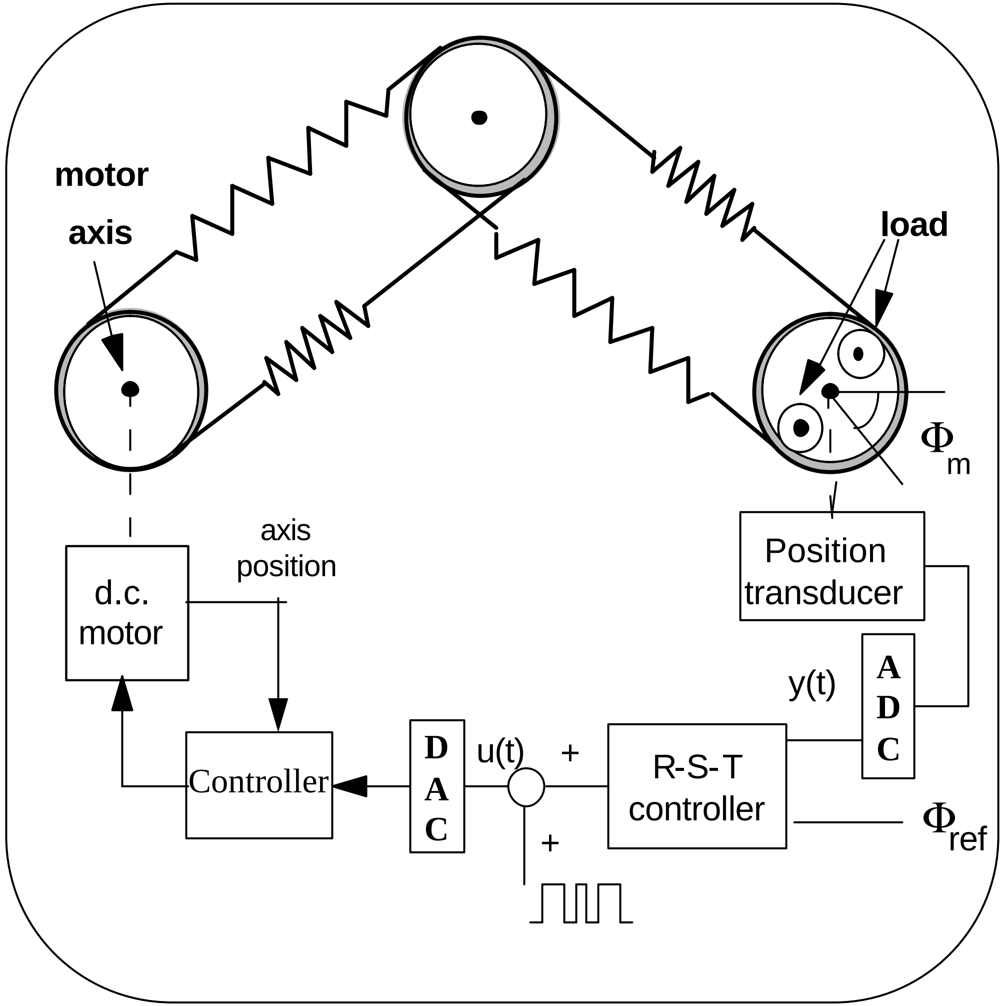
Iterative identification and controller redesign

May provide better « design » models

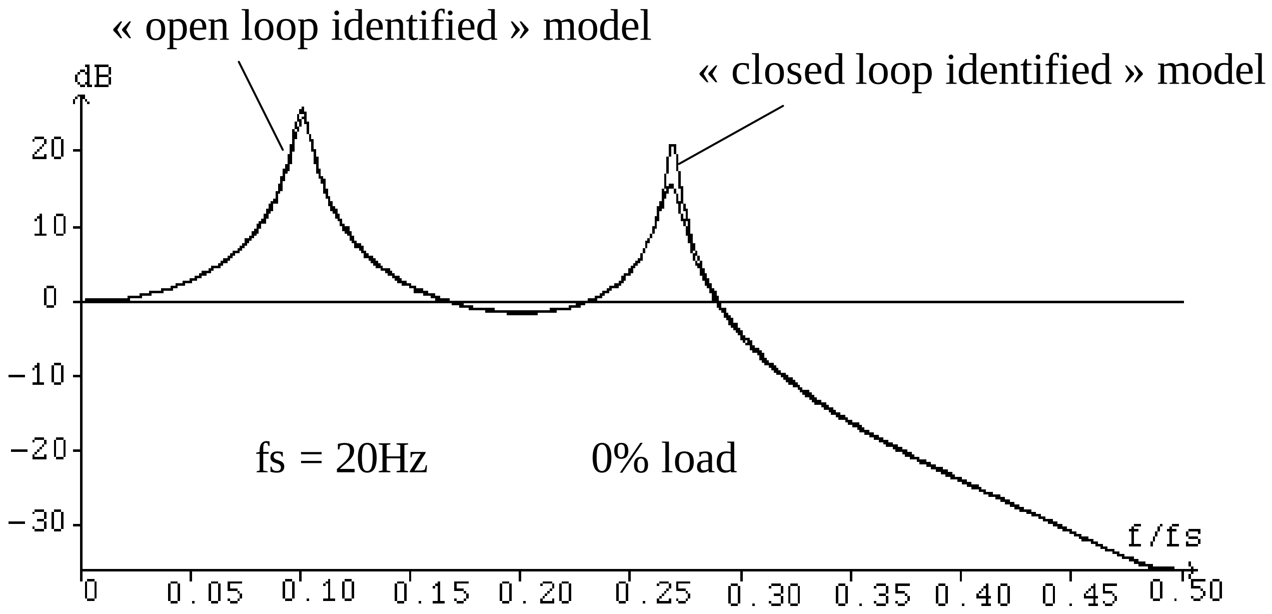
Cannot be dissociated from the controller and robustness issues

Identification in Closed Loop

The flexible transmission

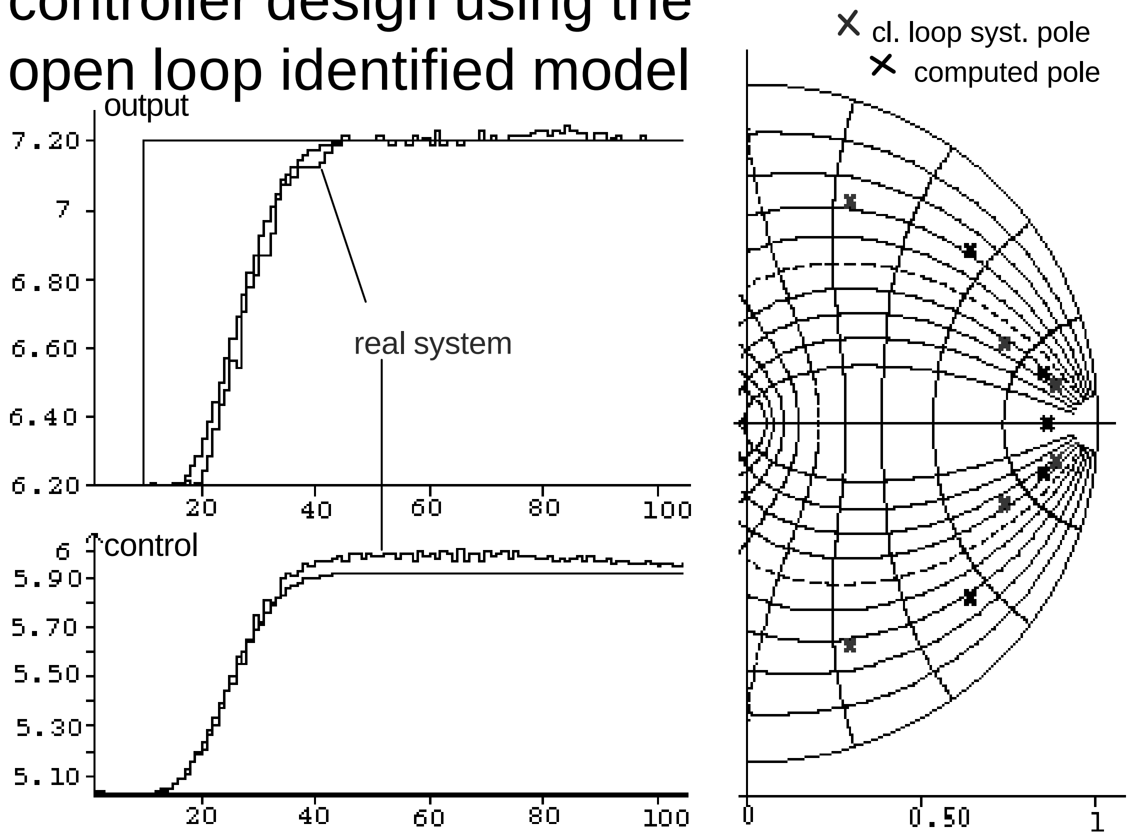


What is the *good* model ?



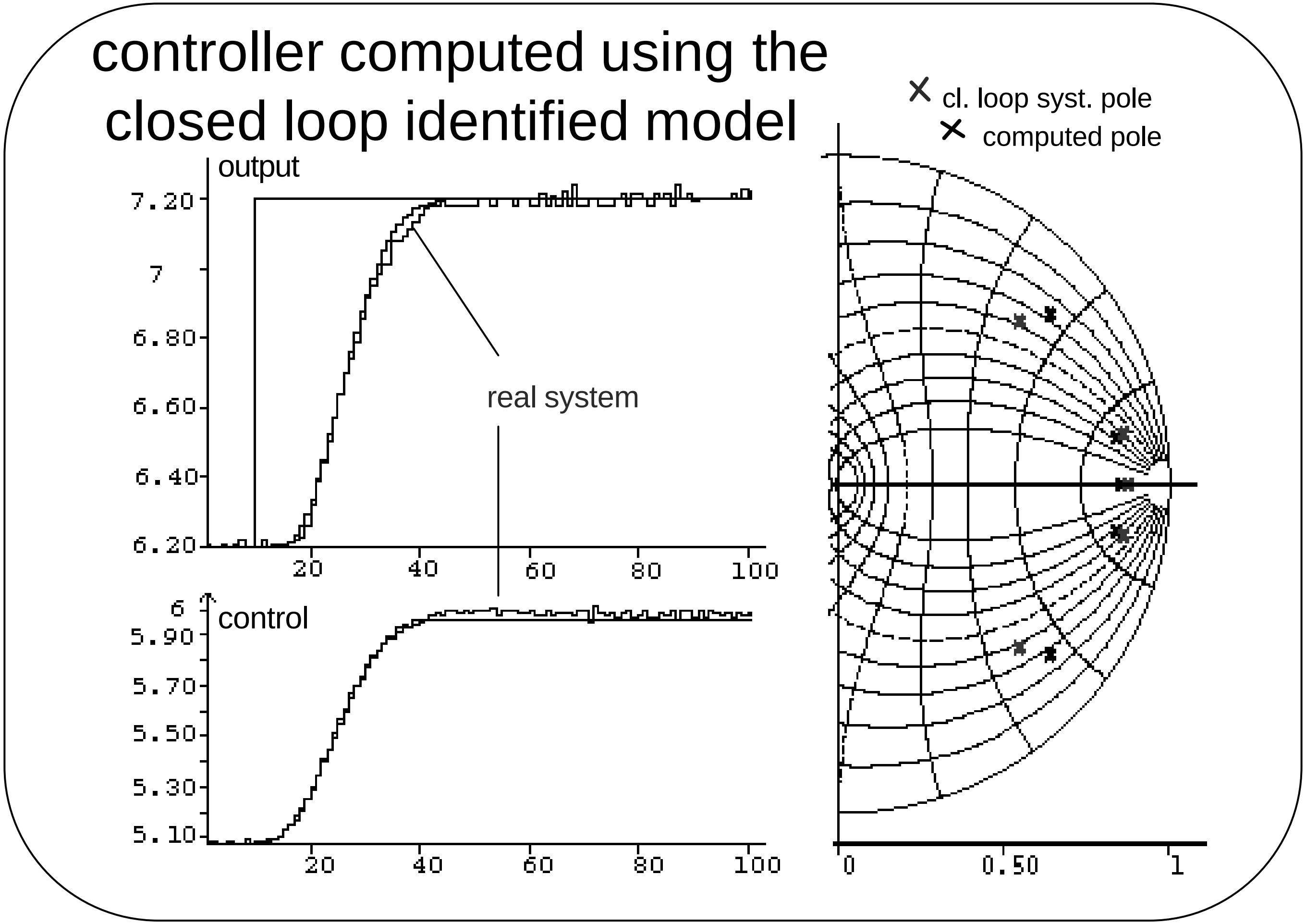
Benefits of identification in closed loop (1)

controller design using the open loop identified model



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

Benefits of identification in closed loop (2)

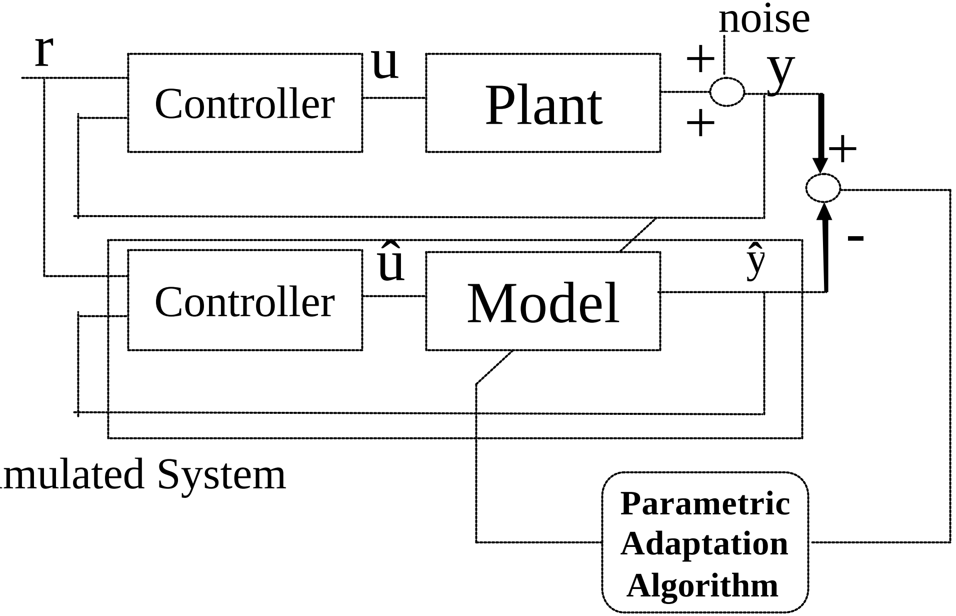


The *computed* and the *identified* closed loop poles are very close

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.

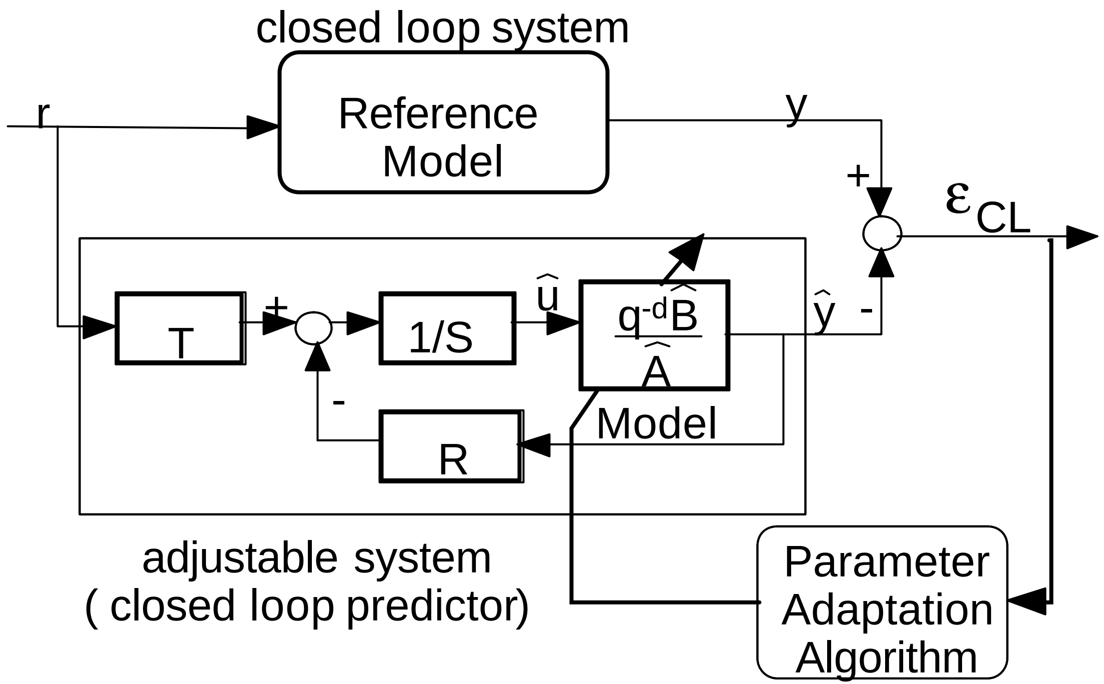


CLOE Algorithms

Closed Loop Output Error

Identification in Closed Loop

- *M.R.A.S. point of view :*



- *Identification point of view :*

A re-parametrized adjustable predictor of the closed loop

Controller reduction

- **Controller reduction is an important issue**
- **Identification in closed loop provides efficient algorithms for controller reduction**

CONTROLLER REDUCTION. Why ?

- Complex Models
- Robust Control Design

→ High Order Controllers

Example : The Flexible Transmission
(Robust control benchmark, EJC no. 2/1995 and no.2-4/1999)

Model complexity : $G(q^{-1}) = \frac{q^{-d}B(q^{-1})}{A(q^{-1})}$ $n_A = 4$; $n_B = 2$; $d = 2$

Fixed controller part : Integrator

Pole placement design : $K(q^{-1}) = \frac{R(q^{-1})}{S(q^{-1})}$ $n_R = 4$; $n_S = 4$

Complexity of controllers achieving 100 % of specifications:

Max : $n_R = 9$; $n_S = 9$ (Nordin) **Min** : $n_R = 7$; $n_S = 7$ (Langer)

CONTROLLER REDUCTION. Why ?

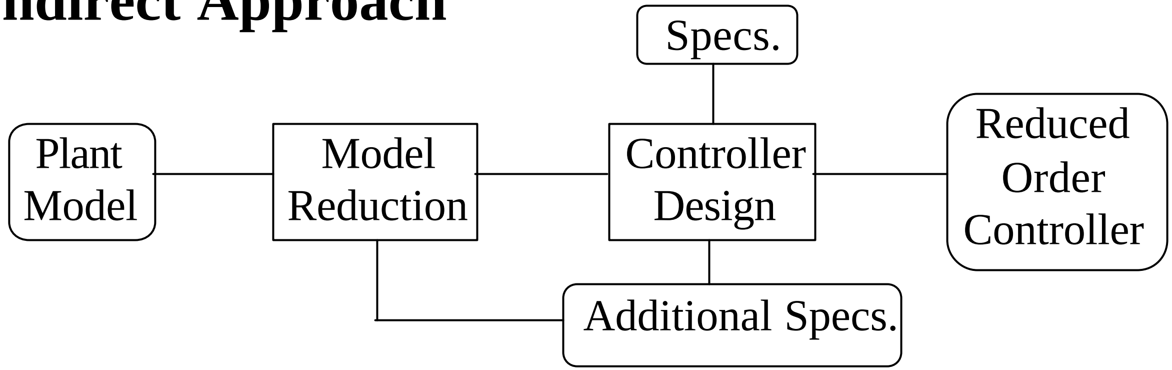
- Mass production (like cars) requires simpler controllers (price constraint)
- Low cost applications require simpler controllers (computer power constraint)
- Even advanced applications require constrainted complexity controllers (computer power constraints)

Complexity of the resulting controller has became part of the design problem

For a « state of the art » see European Journal of Control, no.1, 2003
(web : www.elet.polimi.it/ejc)

Approaches to Controller Reduction

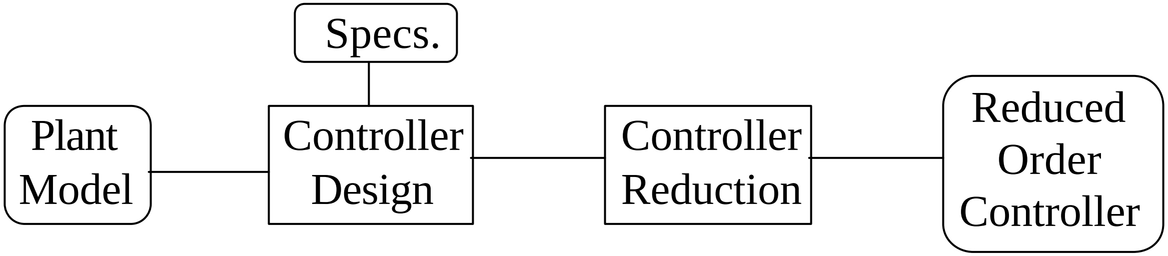
Indirect Approach



-Does not guarantee resulting controllers of desired order

- Propagation of model errors

Direct Approach



- Approximation carried in the final step
- Further controller reduction for "indirect approach"

Controller Reduction

Basic rule :

Controller reduction should be done with the aim to preserve as much as possible the closed loop properties.

Reminder :

Controller reduction without taking into account the closed loop properties can be a disaster !

Some basic references :

- Anderson &Liu : IEEE-TAC, August 1989
- Anderson : IEEE Control Magazine, August 1993

Rem: Direct design of constrained complexity controllers is still an open problem

Identification in Closed Loop and Controller Reduction

- Identification in closed loop is an efficient tool for *control oriented model order reduction*

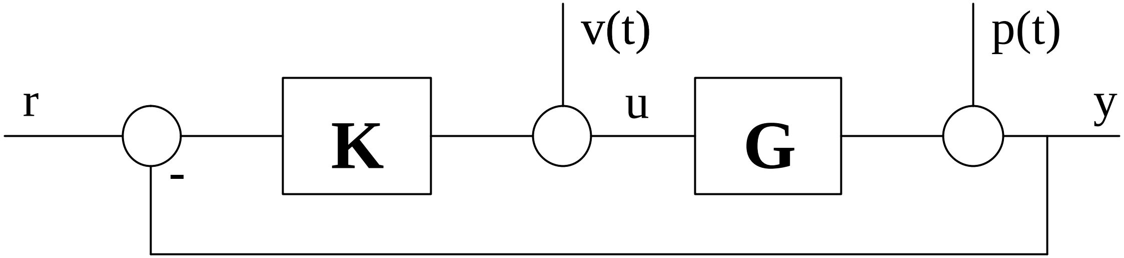
- **Closed loop identification techniques can be used (with small changes) for *direct estimation of reduced order controllers***

Duality

Identification of reduced order models in closed loop ⟷ Identification of reduced order controllers in closed loop

- Possibility of using “real data” for controller reduction

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

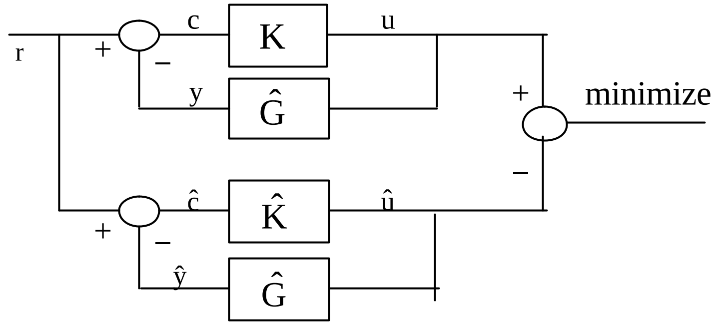
True closed loop system :(K,G), P, S_{xy}

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

Simulated C.L. using reduced order controller : $(\hat{K},\hat{G})$, $\hat{\hat{P}}$, $\hat{\hat{S}}_{xy}$

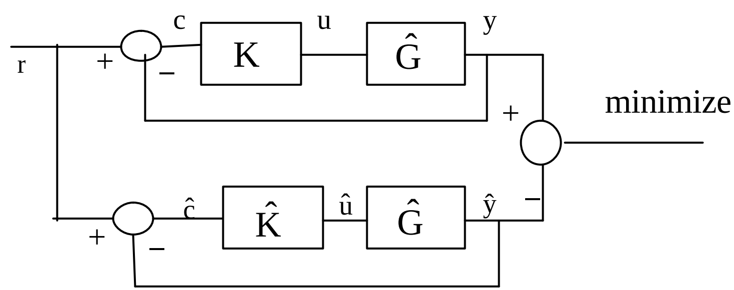
Controller Reduction - Objectives

Input matching



$$\hat{K}^* = \arg\min_{\hat{K}} \left\| \hat{S}_{up} - \hat{\hat{S}}_{up} \right\| = \arg\min_{\hat{K}} \left\| \hat{S}_{yp} (K - \hat{K}) \hat{\hat{S}}_{yp} \right\|$$

Ouput matching

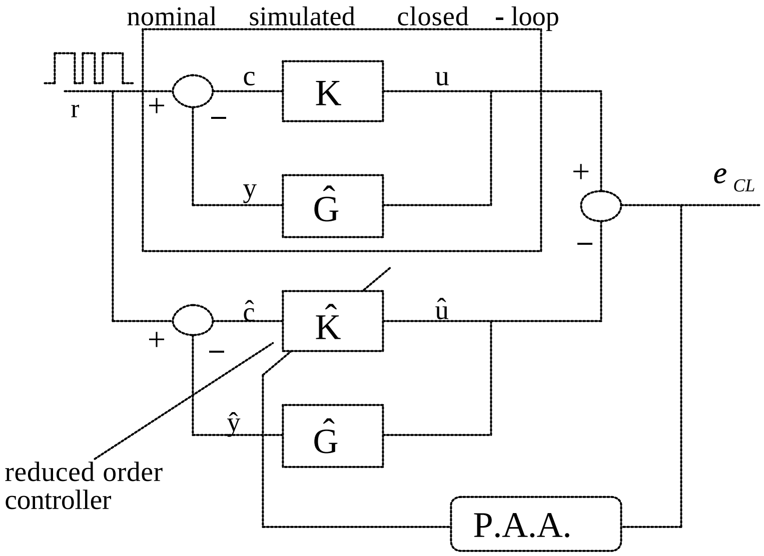


$$\hat{K}^* = \arg\min_{\hat{K}} \left\| \hat{S}_{yr} - \hat{\hat{S}}_{yr} \right\| = \arg\min_{\hat{K}} \left\| \hat{S}_{yp} - \hat{\hat{S}}_{yp} \right\| = \arg\min_{\hat{K}} \left\| \hat{S}_{yp} (K - \hat{K}) \hat{\hat{S}}_{yv} \right\|$$

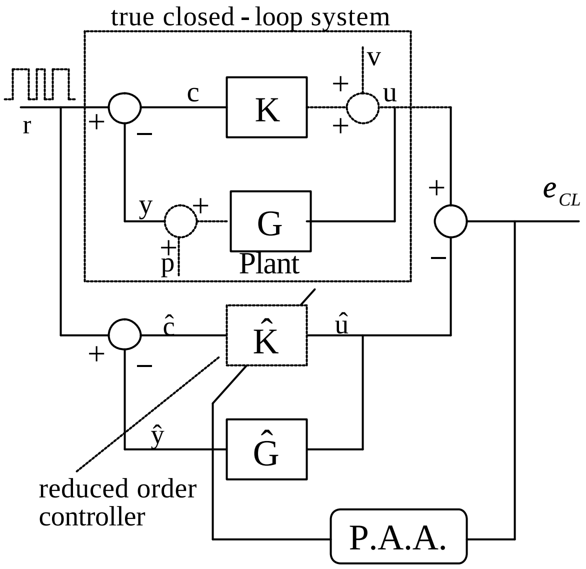
Identification of Reduced Order Controllers

Input Matching (CLIM)

Use of simulated data



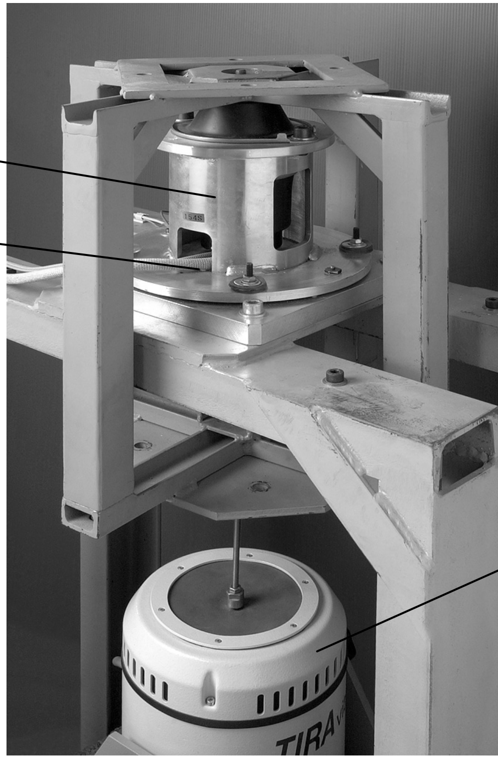
Use of real data



The Active Suspension

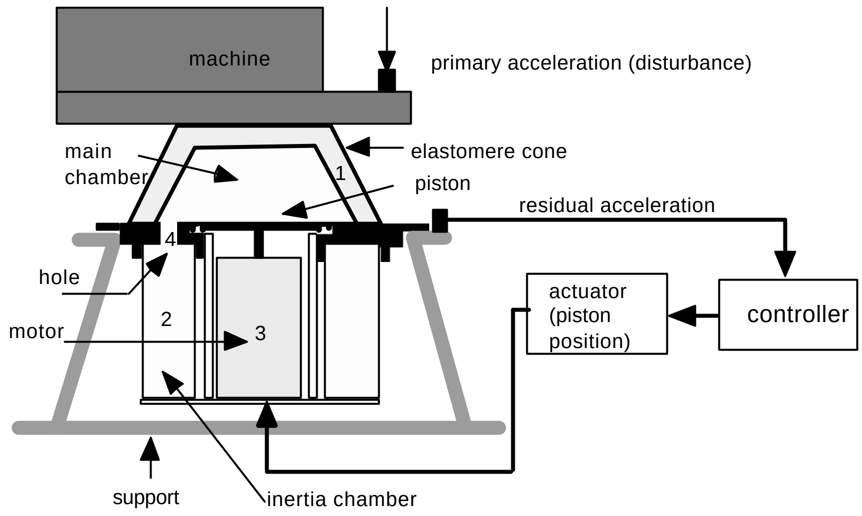
Active suspension

Residual force (acceleration) measurement

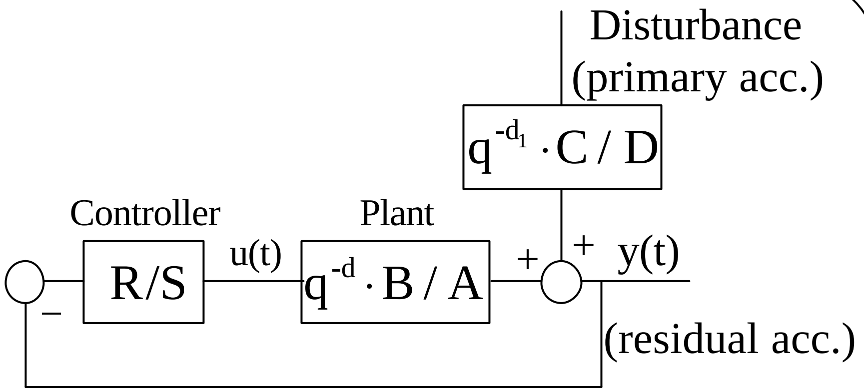


Primary force (acceleration) (the shaker)

Experimental Results - Control of an Active Suspension



- controller: PC
- sampling freq.: 800 Hz

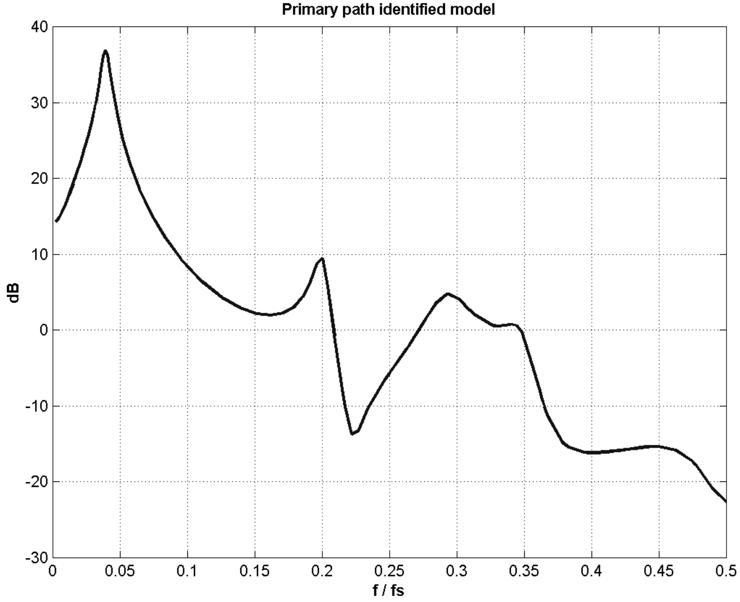


Interesting frequency range for vibration attenuation: 0 - 200 Hz

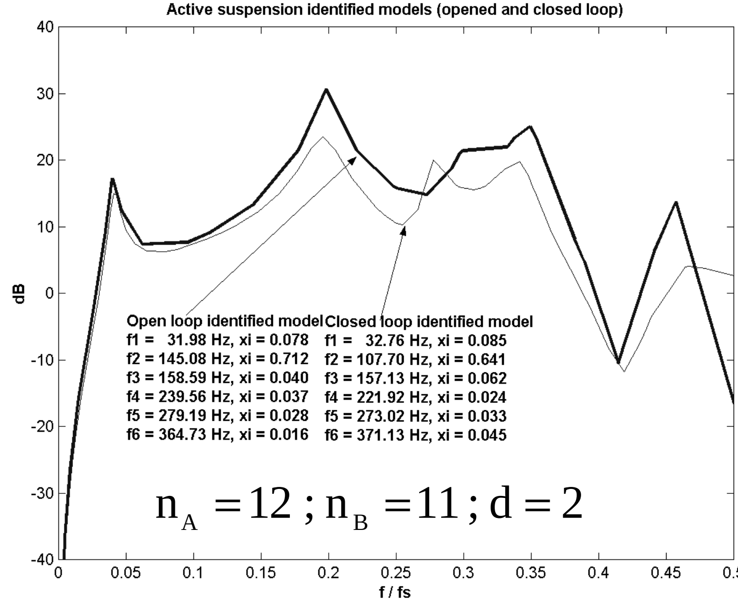
Active Suspension

Frequency Characteristics of the Identified Model

Primary path



Secondary path



Control objectives :

- Minimize residual acc. around first vibration mode
- Distribute amplification of disturb. over high frequency region

- Open loop identified model (design model)
- Closed loop identified model used for controller reduction (better C.L. validation)

The Nominal Controller

Important attenuation of S_{yp} at the frequency of the first vibration mode (32 Hz)

Design method: Pole placement with sensitivity shaping using convex optimization

Dominant poles : first vibration mode with ξ=0.8 (instead of 0.078)

Opening of the loop at 0.5f_s : $H_R = 1 + q^{-1}\,;\,(R = H_R R')$

Nominal controller complexity : $n_R = 27\,;\,n_S = 28$

Pole placement complexity : $n_R = 12\,;\,n_S = 13$

Direct Controller Reduction

CLIM algorithm/ simulated data

Spectral density of the residual acceleration (performance)