TECHNOLOGY - METHODOLOGY

1955+
Operational amplifier
µA709 !

Electric circuits.
Frequency domain

PID

1970
Digital computer

Modelling  Simulation
Identification

MBPC ...PFC
End of the Sixties:

- ORIGIN OF MODEL BASED PREDICTIVE CONTROL
- PETROLEUM INDUSTRY / DEFENCE INDUSTRY

.Refineries:

How to handle constraints on MV’s and CV’s?
How to control a multivariable process?

.Defence:

How to control a process with a non stationary set point with no lag error (follow-up servo)?
....the past...

1968 : Basic principles of Predictive Control
1973 : 1st version of PFC/IDCOM
1974 : 1st industrial applications of PFC/IDCOM
        Steam Generator/ Reactor/ Distillation
1978 : 1st contribution MPC “Automatica “ ( problems..!)
1980-85 : HIECON with Set Point ( Houston)
1989 : Extension from PFC to PPC:
        Parametric Predictive Control  (control by reactor flow..)
TARGET

« Easy to Understand, to Implement, to Tune »

- Solve what PID cannot solve, but in continuity with PID.....
- Control parameters with a clear physical meaning.
- No explicit integrator in the loop
- No matricial calculus
- No iterative minimisation on line
- Open technology....
- Fits with industrial specific control needs!
Pr

\[ P = \frac{G e^{-\theta s}}{1 + Ts} = M = \frac{y}{u} \]

\[ \theta = Tsamp \cdot r \]

\[ y(n) = \alpha y(n-1) + (1 - \alpha) \cdot u(n-1-r) \cdot G \]

\[ \alpha = e^{-\frac{Tsamp}{T}} \]

Trajectory expo. : \( \lambda \)

1 coincidence point: \( H \)

1 Base function: step

Processus with delay

\[ y_{Pr}(n) = y_{P}(n) + y_{M}(n) - y_{M}(n-r) \]

Target : \[ \Delta P(n+H) = (C - y_{Pr})(1 - \lambda^H) \]

Model : Model increment :

Free mode \[ y_{M}(n) \alpha^H \]

Forced mode \[ u(n) \cdot GM(1 - \alpha^H) \]

Control equation :

\[ \Delta P(n+H) = \Delta M(n+H) \]

\[ (C - y_{Pr}(n)) (1 - \lambda^H) = y_{M}(n) \alpha^H + u(n) \cdot GM(1 - \alpha^H) - y_{M}(n) \]

Increment = Free(n+h) + Forced(n+h) - ymodel(n)

The only mathematical problem for trainees ...!
4 BASIC PRINCIPLES OF PFC : J. PIAGET

- Operating Image
- Target – Sub Target
- Action
- Comparison :
  - Predicted / Actual

- Internal independant Model
- Reference Trajectory
- Solver. Functional basis
  Structured future MV
- Error compensator

Natural Control : “You would not drive your car using a PID scheme”
FIRST INDUSTRIAL APPLICATIONS OF P.F.C.

DEFENCE

- Mine hunter
- Ariane 5 attitude control
- Missile autopilot
- Laser guided missile (t=62 microsecond…)
- Gun turrets
- Radar antennas
- Infra Red camera
- High speed Infra Red
- Missile launch
- Camera mount
- Radar antennas
- Laser mirror
- Tank turret (T. 55)
- Mine sweeper auto-pilot
- Aircraft carrier auto-pilot

AUTOMOTIVE

- Gear box test bench
- Dynamic test bench engine
- Fuel injection
- Idle fuel injection
- Clutch antistroke
- Gear box (tank)
- Hybrid car (electric-fuel)
- Air conditioning

METALLURGICAL INDUSTRIES

- Coating lines aluminium
- Thickness control - Roll eccentricity
- Mono-multi-stands Rolling mills
- Continuous casting (slab)
- Push-ovens
- Coke furnace
- Hot/cold/Thin rolling mills
- Steam generators

MISCELLANEOUS (Chem reactors and distillation excluded)

- Bioreactor Melissa ESA
- Plastic extrusion robot (high speed)
- Temperature control of gas furnace
- Temperature control of TGV train carriage
- River dam level control (T=1 hour)
- Powder milk dryer
- Electric furnace brazing etc….

...the oldest MBPC... 1968
A “few” thousands applications in many fields
EXOTIC APPLICATIONS…

North : Molde (Norway)
South : Plaza Huincul (Patagonia-Argentina)
East : Hokaido (Japan)
West : Mobile (USA.DEGUSSA)
High : Eiffel Tower elevator!
Space : European Space Agency: Mars project bioreactors (2029!)
Depth : Mine hunter boat
Speed : Temperature cabin (TGV: 574.8 km/h W.record)
Fast : Laser guided bomb (Tsampling: 65 μs)
Slow : River dam level (Tsampling: 1 hour / FP model on line)
Ecology: Diester from colza
Animal : Dog food pellet dryer
Plants : Greenhouses
etc…
AT WHAT LEVEL DO WE OPERATE?

Back to Basics:

• Level 0: Ancillary processes e.g. FIC/ Pid (the valve is the nightmare of control!)
• Level 1: Dynamic control with constraints
• Level 2: Optimization of working conditions
• Level 3: Production planning

Level N is operative if level N-1 works well...!

»There are no technical problems, but only technical aspects of economic problems... »
TARGETED PERFORMANCES

- Control « all » types of processes: time delay, unstable, non-minimum phase, some non-linear,
- Handles all constraints on the MV and on internal variables of the process CV.
- No lag error on dynamic set points with no integrator
- Transparent and Cascade Control with transfer of constraints from inner loop to outer controller (« Back Calculation »)
- True feed-forward
- Split-range control with different dynamics (reactors!)
- Control with 2 cooperative MV’s, e.g., big valve / small valve
- Extendable to 3 MV/ 3 CV.....
- Dual control: total elimination of harmonic disturbances
- Full Robustness analysis: easy trade-off,
- Immediate tuning / Open technology

Etc.....
2 TYPES OF MODELS

Independent models are selected:

- Input /Output models valid for all math. structures

- No permanent errors in steady-state modes!
  (never mix process variables with model parameters..)
TEST PROTOCOL OPTIMIZATION

APPLY AN « OPTIMAL » TEST INPUT SIGNAL TO VALIDATE A MODEL OF THE PROCESS ? : SEQUENCE OF TESTS OF DIFFERENT DURATIONS

- LIMITED AMPLITUDE : BETWEEN +M / - M ?

- LIMITED DURATION H : H < NEGOCIATED TIME ?

- SENSITIZING SPECTRUM DEPENDING ON THE BAND PASS OF THE PROCESS ?

IT IS POSSIBLE TO OPTIMIZE THE PROTOCOL : MINIMUM UNCERTAINTY OF THE PARAMETERS OF THE PROCESS IF WE KNOW THE PROCESS:

Solution ? : ITERATIVE TEST PROCEDURE

PRBN : not realistic !
Solver

• The future MV is projected on a Functional Basis:
  – e.g. Taylor expansion / Polynomials
• Thus, the MV is restricted *a priori* and not damped afterwards....
• \( MV(n+i) = \sum \mu_j \cdot U_j(i) \)
• \( U_0(i) = 1, \quad U_1(i) = i \quad U_2(i) = i^2 \quad \text{etc} \quad ... \)
• Find the \( \mu_j \) such that:
  – At a finite number of points, the predicted model output coincides with the desired reference trajectory
    • (i.e., coincidence points)
Why structuring the future MV?

• Computing all future MVs is of little benefit:
  Computation time increases (PLC!)
• Introduction of a damping term on the speed of
  the MV *a priori* is difficult to tune!
• So....
• Projection on «Eigen» MV functions of linear dynamic processes insures no lag
  error on dynamic set points
ACCURACY

• Basic Eigen Function property:

• If the set point can be projected on a polynomial basis of order N, and if the non integrative model is of order N, then there is no lag error…!

• Accuracy depends on the choice of the functional basis and not on the “gain” of the controller....
Let us take an exemple!

- 95% of pharma drugs are crystals!
- According to Professor’s Mullin’s theory the temperature time profile during crystalisation should be close to a cubic function!

Challenge .. !

SANOFI: 6 production plants > 1200 PFC installed in different control PLC’s
VIT210809a - Pente de refroidissement Mullin ordre 2.5 de 70°C à 20°C équivalent à une rampe de 10°C/h
Erreur de trainage entre la consigne de température masse demandée et la température masse réelle
4 CONTROL STRATEGIES OF BATCH REACTORS

1) \( F_i = \text{ct} \) \( \rightarrow \) \( \text{MV}=T_i \) \( \rightarrow \) \( \text{CV}=T_M \) \( \rightarrow \) level 0 \( \rightarrow \) Ti ? \( \rightarrow \) :PFC

2) \( T_i = \text{ct} \) (!) \( \rightarrow \) \( \text{MV}=F_i \) \( \rightarrow \) Parametric Control non linear \( \rightarrow \) :PPC

3) \( \text{MV} \) : \( \textbf{Ti} \) and \( \textbf{Fi} \) : Enthaplic control (power) \( \rightarrow \) :PPC+

4) \( \text{MV} \) : Pressure of reactor \( \rightarrow \) :PFC

\[
\begin{align*}
\dot{T}_M &= \frac{dT}{dt} = \frac{M}{M} (T_e - T_e) + DHx \\
&= r e C_p V_e \frac{dT_e}{dt} = r e F_i(T_i - T_e) + UA (T_M - T_e)
\end{align*}
\]

\[
q(F_i) \quad \dot{T}_M + T_M = T_i
\]
The Tea Pot theory

- Heat transfer with heat loss?:
- What to do?
  « To heat up slowly during a long time or abruptly during a short time »

- « Energy consumption is minimum if Power is maximum »
\[ F \cdot T = F_1 \cdot T_1 + F_2 \cdot T_2 \]
\[ T = \lambda \cdot T_1 + (1 - \lambda) \cdot T_2 \]
\[ \lambda = \frac{F_1}{F_1 + F_2} \quad 0 \leq \lambda \leq 1 \quad \text{Hyperbolic function} \]
\[ \Gamma(Q_f) = \frac{1 - \exp[-U.A\left(\frac{1}{F_p} - \frac{1}{F_f}\right)\frac{F_p}{F_f}]}{1 - \frac{F_p}{F_f}\exp[-U.A\left(\frac{1}{F_p} - \frac{1}{F_f}\right)\frac{F_p}{F_f}]} \]

\[ F_p, F_f : \text{Thermal flows} \]

\[ F_p = (\rho.C_p)_p.Q_p \quad F_f = (\rho.C_p)_f.Q_f. \]
EXOTHERMICITY ESTIMATOR
by Global estimator

\[ \text{Cons1} \rightarrow R1 \rightarrow \text{MV1} \rightarrow P \rightarrow SP \]

\[ \text{Cons2} = SP \rightarrow R2 \rightarrow \text{MV2} \rightarrow \text{M} = P \rightarrow SP^* \]

\[ \text{Pert} \rightarrow \]

\[ B \rightarrow \]

\[ \text{Pert}^* \rightarrow \]
STRUCTURE and STATE DISTURBANCES

• On line global estimator: an example!
  \[ DV(n) = \text{actual disturbance} \]
  \[ DV^*(n) = \text{estimated disturbance} \]
  \[ G_p = 1/ \text{gain of process} \]
  \[ G_m = 1/ \text{gain of model} \quad \text{(same dynamics...)} \]
  \[ DV^*(n) = DV(n) + \text{Setpoint}.(G_m-G_p) \]

State and structure mismatches in the same equation!
**BAYER**

$V_m = 42.3 \text{ m}^3$

$F = 250 \text{ m}^3/\text{H}$  \hspace{1cm} $A = 85 \text{ m}^2$  \hspace{1cm} $U = 450 \text{ W/m}^2/\text{K}$

$\text{NUT} = .135$

$\Theta_s = 610 \text{ sec}$  \hspace{1cm} $\tau_m = 5370 \text{ sec}$
TEMPERATURE DE MASSE

Figure 4

Tmax = 108.4°

92°

Tinit = 42°

d°
ESTIMATION DE L’EXOTHERMICITE

Figure 3
SANOFI PHARMA

NEUTRALISATION WITH ON LINE ESTIMATOR OF EXOTHERMICITY TAKEN INTO ACCOUNT AS A FEED FORWARD VARIABLE

2 CONTROLLERS ARE ACTIVE:

- ONE TO CONTROL THE TEMPERATURE ... AS USUAL...

- ONE TO CONTROL THE REACTION ACTIVITY MEASURED BY THE ON LINE ESTIMATOR OF POWER ACTING ON THE FLOW OF REACTANT.........

soft sensor...!
Réaction - Coulée du BBr3

Temps (min)
PFC / PPC : DEGUSSA EVONIC

- Esterification : Batch time reduced approx. 10%
- Polymerisation: Time duration 15% shorter
- Quality . Reproducability increased
- Less energy consumption
- Implemented in all types of PLCs

01/12/2011 > 300 processes in several plants in different countries
Batch Reactor Control by Jacket flow as MV
Identification of characteristics

\[ \tau = \frac{a + b \cdot Q_f}{Q_f} \]

\[ a = V_m + V_f \]

\[ b = \frac{\rho \cdot cp \cdot V_m}{U \cdot A} \]

- \( Q_f \): flow
- \( V_m \): mass volume
- \( V_f \): jacket volume
- \( \rho \): density
- \( cp \): heat capacity
- \( U \): constant
- \( A \): heat transfer surface
Control with PID

39 different batches with PID
Process control with PPC

32 different batches with PPC

\[ \pm 0.2 ^\circ \text{C} \]
Continuous casting

Level control:

Known as a difficult and dangerous process
Harmonic swell of steel in the extraction cooling section called « Bulging »

Solution:
Implementation of complex algebra in the PLC to control with only one « complex PFC » the sinusoidal disturbance.

Simplification of the controller …
poche de 335 t d'acier liquide à 1550 °C

busette rotative

quenouille

mesure de position

verin

mesure de niveau

PFC

PI

amplificateur de puissance

capteur radio-actif

ingotière à largeur variable

850-2200 mm, reffroidie à l'eau

cages d’extraction

distributeur de 60 t

consigne de poids

mesure de poids

busette à 2 ouïes

consigne=70%
Teaching Control in Technical schools

- 39 Technical schools in France
- ≠ 660 Young technicians per year
- PFC was taught to 23 profs of Tech. schools
- Lectures and laboratory works on PLCs and laboratories processes.
- The first 125 young technicians went out to industry in 2007, completely at ease with PFC...
- 22 profs of German Fachhochschule were trained on PFC in 2009
THANK YOU FOR YOUR ATTENTION
Scheme AHU LT22: Treatment of Air after Mix chamber

Flow fresh air: 20,000 m³/h
Flow recirculated air: 10,000 m³/h

Flow Outgoing air:
20,820 m³/h

Flow Outgoing air:
18,580 m³/h

Flow recirculated air:
9,180 m³/h