Process Dynamic Modelling

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Session Outlines & Objectives

Outlines

- What is dynamic modeling?
- Why do we need dynamic models?
- Dynamic modeling methods
- Mathematical dynamic modeling of controlled processes

Objectives

- The importance of process dynamic
- Know the methods used to model a process
- Know various type of common mathematical dynamic model of industrial process

Dynamics vs. Steady State Model

- Chemical process are generally designed from a steady-state point-of-view
  - Steady state model
    - Steady state: No further changes in all variables
    - No dependency in time: No transient behavior
- Chemical processes are dynamically changing continuously
  - Dynamics is the time varying behavior of processes
- Steady-state change indicates where the process is going and the dynamic characteristics of a system indicates what dynamic path it will take

Why do we need dynamic model?

- People's emotion: An Everyday Example of Dynamic Modelling

Do we give the same approach to handle both situations?

- What is your objective?

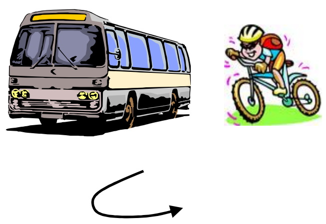
Laughing

Mad

Why do we need dynamic model?

Do the bus and bicycle have different dynamics?

- Which can make a U-turn in 1.5 meter?
- Which responds better when it hits a bump?



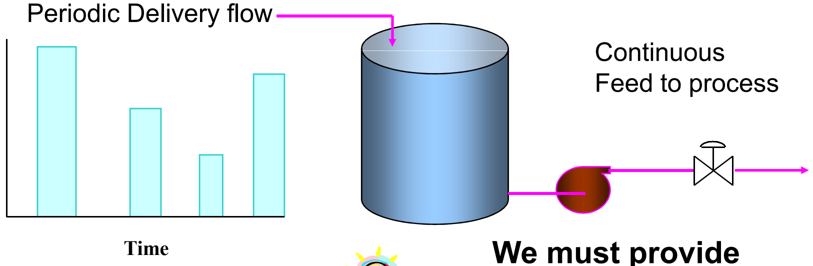
Dynamic performance depends more on the vehicle than the driver!

The process dynamics are important than the computer control!

Why do we need dynamic model?

Feed material is delivered periodically, but the process requires a continuous feed flow

- How large should the tank volume be?

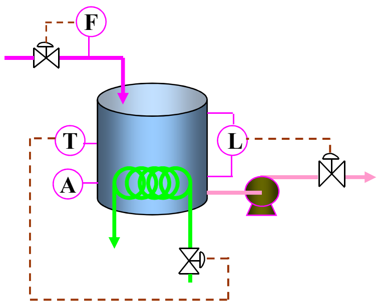


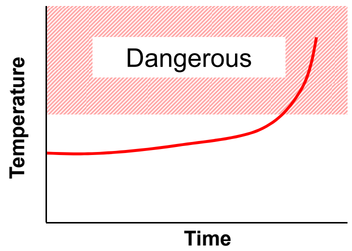
We must provide process flexibility for good dynamic performance!

Why do we need dynamic model?

The cooling water pumps have failed

- How long do we have until the exothermic reactor runs away?





Process dynamics are important for safety!

Why do we need dynamic model?

- In order to be able to design a controller, to achieve a specific objective, for the system under concern we **must** know which system we are dealing with
  - The process dynamics are important than the computer control
    - To improve understanding of the process
    - To select the right controller
  - We must provide process flexibility for good dynamic performance
    - To optimize process design/operating conditions
    - To accommodate the possibility of the change of process dynamic → **ROBUST!**
  - Process dynamics are important for safety

How to Obtain a Dynamic Model?

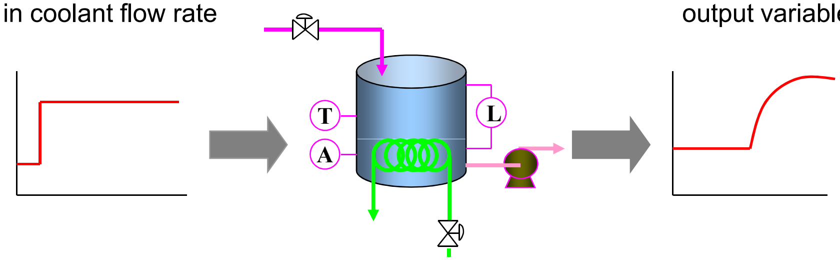
- Model can be described using verbal, table, <u>mathematic</u>, etc.
- The rationale for mathematical modeling
  - To improve understanding of the process
  - To train plant operating personnel
  - To design the control strategy for a new process
  - To design the control law
  - To select the controller setting
  - To optimize process operating conditions
- Main mathematically modeling methods:
  - Physical modeling
    - Based on physicochemical law
  - Identification
    - Based on process data analysis
  - Semi-empirical models
    - Combined approach

Why do we develop mathematical models?

Input change, e.g., step in coolant flow rate

Process

Affect on output variable



How does the process input influence the response?

- How far?
- How fast
- "Shape"

Math models help us answer these questions!

Physical modelling (1)

- Total mass balance

  [Rate of mass accumulation within CV] = [Rate of mass in from surroundings] – [Rate of mass out to surroundings]

- Component mass (molar) balance

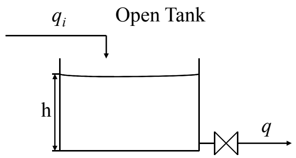
  [Rate of mass accumulation within CV] = [Rate of mass in from surroundings] – [Rate of mass out to surroundings] + [Rate of mass creation within CV]

- Total energy (enthalpy) balance

  [Rate of energy accumulation within CV] = [Rate of energy in from surroundings] - [Rate of energy out to surroundings]

Physical modelling (2)

- Illustrative Example: Open Liquid Storage Tank



Total mass inside CV = $\rho A h$

Rate of Mass Accumulation inside CV = $\frac{d(\rho A h)}{dt}$

Rate of mass into CV by flow = ρq_i

Rate of mass out of CV by flow = ρq

$$\frac{d(\rho A h)}{dt} = q_i\rho - q\rho \quad \Rightarrow \quad \rho A\frac{dh}{dt} = q_i\rho - q\rho$$

Physical modelling (3)

- Follows conservation laws
- Requires a specific expertise
- Difficult to develop
- Expensive
- Time consuming
- Too complex model
- Found in the fields that need accurate model, e.g. aerospace shuttle, aircraft

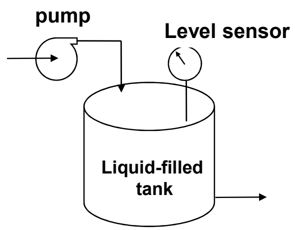
Identification

- Based on the operation data
- Easy to develop
- Requires well designed experimental data
- The behavior is correct only around the experimental condition
- Obtained model obtained usually quite simple for control purpose
- Found in the industrial process control area

Process Dynamic Characteristics

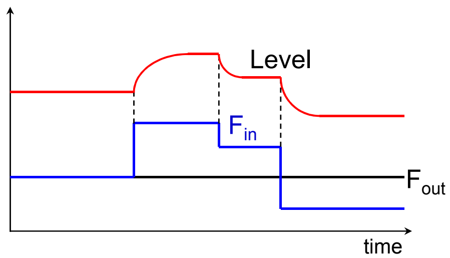
- Self-regulating and non self-regulating
- Lag
    - 1st order
    - 2nd order
    - Higher order
- Dead time
- Interacting and non interacting

Self-regulating process

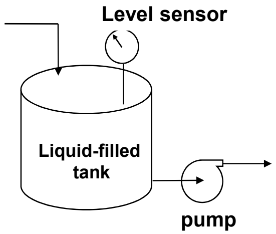


$$\rho \frac{dV}{dt} = \rho A \frac{dL}{dt} = \rho F_{in} - \rho F_{out}$$

- In flow is set independent of level
- Out flow is dependent of level

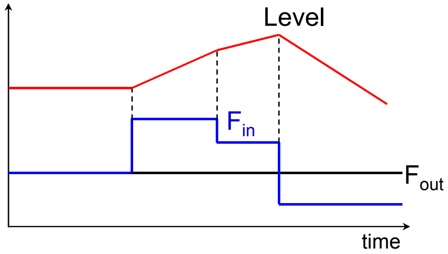


Non Self-regulating process



$$\rho \frac{dV}{dt} = \rho A \frac{dL}{dt} = \rho F_{in} - \rho F_{out}$$

- In flow and out flow are set independent of level
- Also known as Integrating Processes



1st Order Processes (1)

The basic equation is:

$$\tau_p \frac{dy(t)}{dt} + y(t) = K_p u(t)$$

- Differential equation

$$G_p(s) = \frac{K_p}{\tau_p s + 1}$$

- Transfer function

K_p = steady-state gain

τ_p = time constant

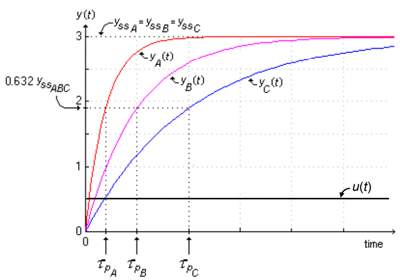
- Note that gain and time constant define the behavior of a 1st order process.

1st Order Processes (2)

- Same K_p, different τ_p

  $K_{pA} = K_{pB} = K_{pC}$

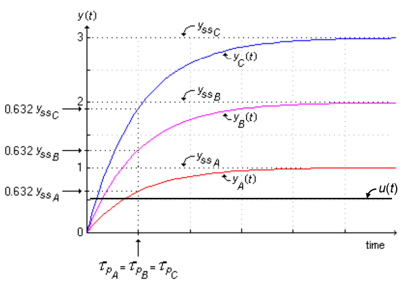
  $\tau_{pA} < \tau_{pB} < \tau_{pC}$



- Different K_p, same τ_p

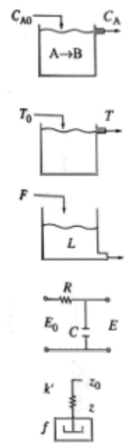
  $K_{pA} < K_{pB} < K_{pC}$

  $\tau_{pA} = \tau_{pB} = \tau_{pC}$



Always overdamped

1st Order Processes (3)



Balance	Input	Output	K_p	τ
Component material	C_{A0}	C_A	$\frac{F}{F+Vk}$	$\frac{V}{F+Vk}$
Energy	T_0	T	1.0	$\frac{V}{F}$
Overall material	F	L	$\frac{1}{0.5kL_s^{-0.5}}$	$\frac{A}{0.5kL_s^{-0.5}}$
Current	E_0	E	1.0	RC
Force	z_0	z	1.0	f/k'

2nd Order Processes (1)

The basic equation is:

$$\tau_p^2 \frac{d^2 y(t)}{dt^2} + 2\zeta \tau_p \frac{dy(t)}{dt} + y(t) = K_p u(t)$$

- Differential equation

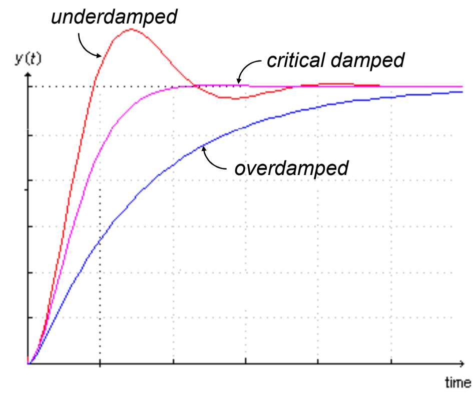
$$G_p(s) = \frac{K_p}{\tau_p^2 s^2 + 2\zeta \tau_p s + 1}$$

- Transfer function

- Note that the gain, time constant, and the damping factor define the dynamic behavior of 2nd order process

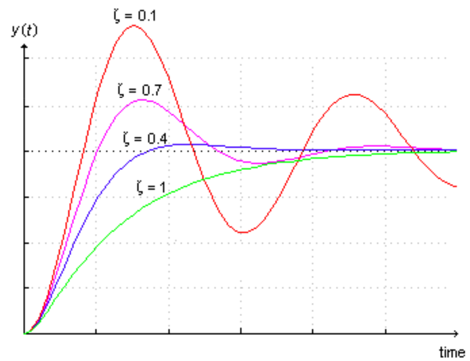
2nd Order Processes (2)

- Underdamped vs. Overdamped



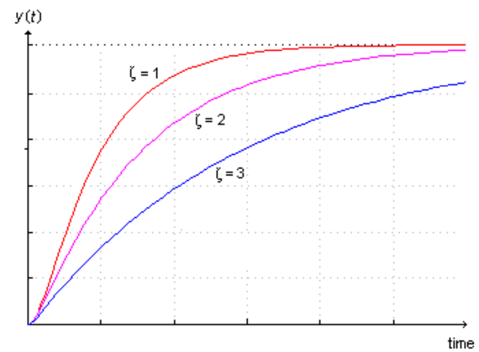
2nd Order Processes (3)

- Effect of ζ on Underdamped Response



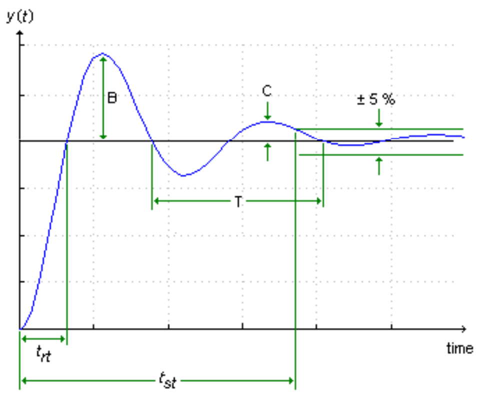
2nd Order Processes (4)

- Effect of ζ on Overdamped Response



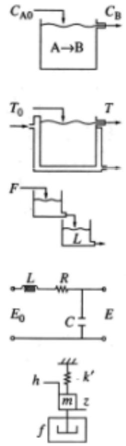
2nd Order Processes (5)

- Characteristics of an Underdamped Response



- Rise time
- Overshoot (B)
- Decay ratio (C/B)
- Settling or response time
- Period (T)

2nd Order Processes (6)



Balance	Input	Output	K_p	τ^2	$2\xi\tau$
Component material	C_{A0}	C_B	$\frac{Vk}{F+Vk}$	$\tau_A\tau_B$	$\tau_A+\tau_B$
Energy	T_0	T	[see question 5.2]		
Overall material	F	L	$\frac{1}{0.5kL_s^{-0.5}}$	$\left[\frac{A}{0.5kL_s^{-0.5}}\right]^2$	2τ
Current	E_0	E	1.0	LC	RC
Force	h	z	$1/k'$	m/k'	f/k'

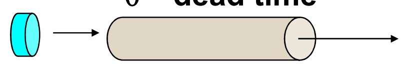
Underdamped Processes

- Many examples can be found in mechanical and electrical system
- Among chemical processes, open-loop underdamped process is quite rare
- However, when the processes are controlled, the responses are usually underdamped
- Depending on the controller tuning, the shape of response will be decided
- Slight overshoot results short rise time and often more desirable
- Excessive overshoot may results long-lasting oscillation

Dead Time

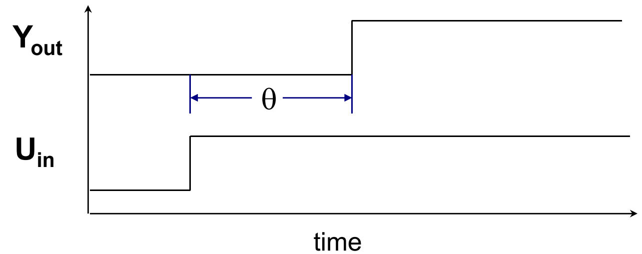
- Fluid transportation through a pipe
  - Also called as distance-velocity lag, transportation lag, time delay

θ = dead time



$$Y_{out}(t) = U_{in}(t-\theta)$$

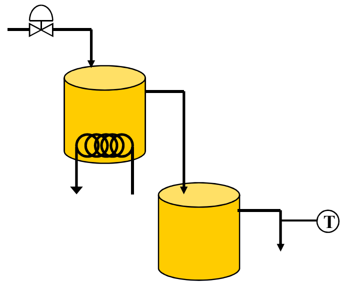
$$Y_{out}(s) = e^{-\theta s}U_{in}(s)$$

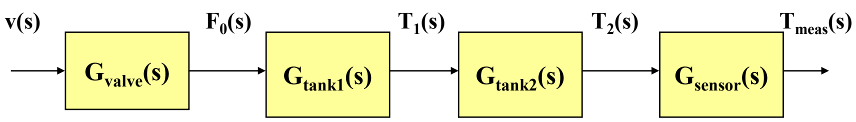


Structure of Process Systems (1)

Non-Interacting Series

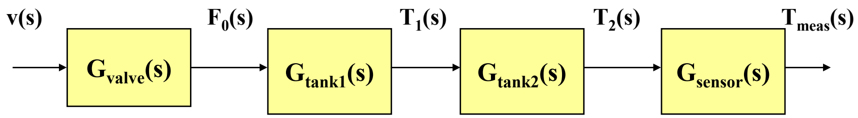
- The output from an element does not influence the input to the same element
- Common example is tanks in series with pumped flow between
- Block diagram as shown





Structure of Process Systems (2)

Non-Interacting Series



In general:

$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} G_i(s)$$

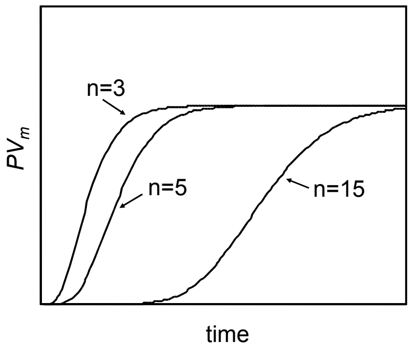
With each element a first order system:

$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} \frac{K_i}{(\tau_i s + 1)}$$

- overall gain is product of gains
- no longer first order system
- slower than any single element

Structure of Process Systems (3)

- High Order Processes



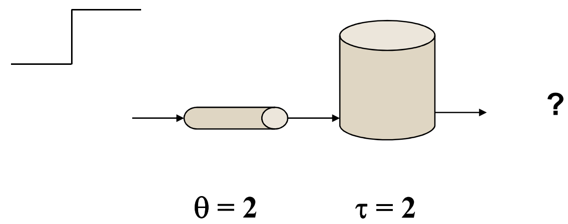
- The larger n, the more sluggish the process response (i.e., the larger the effective deadtime)
- Transfer function:

$$G_p(s) = \frac{K_p}{(\tau_p s + 1)^n}$$

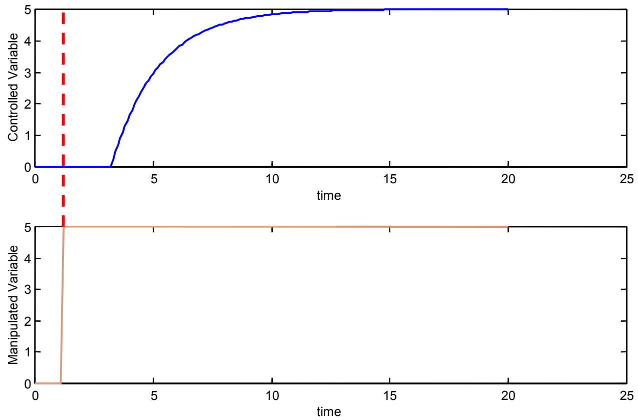
Structure of Process Systems (4)

Exercise:

Sketch the step response for the system below



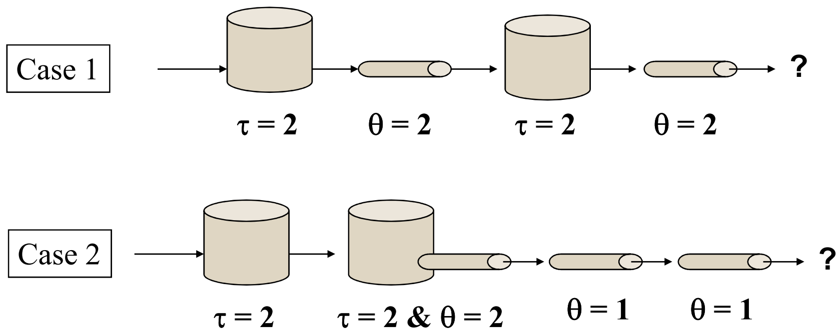
Structure of Process Systems (5)



Structure of Process Systems (6)

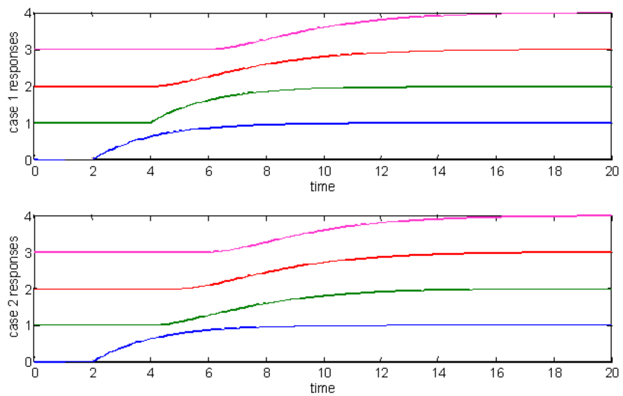
Exercise:

Sketch the step response for each of the systems below and compare the results



Structure of Process Systems (7)

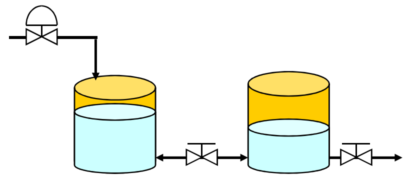
- Two plants can have different intermediate variables and have the same input-output behavior!



Structure of Process Systems (8)

Interacting process

- Many chemical processes exhibit interacting nature
- The output from an element influence the input to the another element and vice versa



Session Summary

- A good understanding on controlled process dynamic is very important to achieve a good control
- Process models can be obtained using physical, identification and combined approaches
- Many industrial processes can be represented by simple mathematical process dynamic, i.e. 1st order, 2nd order (with dead time)