Design and Implementation of the Novel Feedforward Action Smith Predictor (FASP) on the Quadruple Tank Process with Multiple Delays.

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Goals & method

- To check the feasibility and to examine some implementation issues of the Feedforward Action Smith Predictor (FASP) controller.

- Performed by designing and applying the FASP to the Quadruple Tank Process with DTs (QTPwDT) lab setup.

- Compared performances with the state of the art DTC-GMDC

Collaborator – Alexey German

Outline

- MIMO LTI processes with multiple DTs & I/O DTs
- Control of MIMO plants with multiple delays
  - GMDC - state of the art DTC
  - FASP- structure & properties
- FASP- potential implementation difficulties and solutions
- Quadruple-tank process with multiple delays (QTPwDT)
  - The QTPwDT setup
  - Properties of the QTPwDT
- Experimental studies & results
- Summary and conclusions

Processes with multiple DTs

$$P(s) = \left(p_{ij}(s) e^{-h_{ij}s} \right)$$

$P_{ij}(s)$ – a rational transfer function relating input j to output i
h_{ij} - DT between input j and output i

✓ arise naturally in many areas of engineering and sciences.
(sensor networks, autonomous vehicles, biological systems, networked control systems, internet congestion control, farms of wind turbines and more)

Processes with multiple I/O DTs

$$P(s)=\Lambda_y(s)G(s)\Lambda_u(s)e^{-h_c s}$$

G(s) – a rational transfer matrix

$$\Lambda_u(s)=diag\left\{I_{m_0},e^{-s\cdot h_{u,1}}\cdot I_{m_1},\ldots,e^{-s\cdot h_{u,q}}\cdot I_{m_q}\right\} \quad ,$$

$$0<h_{u,1}<\ldots<h_{u,q} \quad , \quad \sum m_j=n_u$$

$$\Lambda_y(s)=diag\left\{I_{p_0},e^{-s\cdot h_{y,1}}\cdot I_{p_1},\ldots,e^{-s\cdot h_{y,r}}\cdot I_{p_r}\right\} \quad ,$$

$$0<h_{y,1}<\ldots<h_{y,r} \quad , \quad \sum p_j=n_y$$

- less general than

$$P(s)=\left(p_{ij}(s)e^{-h_{ij}s}\right)$$

Multiple DTs & multiple I/O DTs

✓ Question: $P(s) = \left(p_{ij}(s) e^{-h_{ij}s}\right) \overset{?}{=} \Lambda_y(s) G(s) \Lambda_u(s)$

➲ Answer: (Sanchez-Pena et al, 2009) - iff

$$h_{iq} - h_{jq} = h_{ik} - h_{jk}, \begin{cases} i = 1,\ldots,m & j = 1,\ldots,m \\ q = 1,\ldots,n & k = 1,\ldots,n \end{cases}$$

Partial extraction of DTs

✓ When it is impossible to extract all DTs to inputs and outputs we may factor (h_{ij}) as follows

$$(h_{ij})_{mxn} = \underbrace{(h_{yi})_{mxm}}_{\bar{\Lambda}_y} (\eta_{ij})_{mxn} \underbrace{(h_{ui})_{nxn}}_{\bar{\Lambda}_u}$$

✓ a partial extraction problem may be defined (German, 2010):

$$J(h_{u1},\ldots,h_{um},h_{y1},\ldots,h_{yn}) = \sum_{i=1}^{m}\sum_{j=1}^{n}\eta_{ij}\ , \qquad \eta_{ij} = h_{ij} - h_{ui} - h_{yj}$$

$$s.t. -\eta_{ij} \le 0; -h_{ui} \le 0; -h_{yj} \le 0$$

➲ J could be minimized with additional constraints on the structure of (η_{ij})

Control of MIMO Plants with Multiple delays

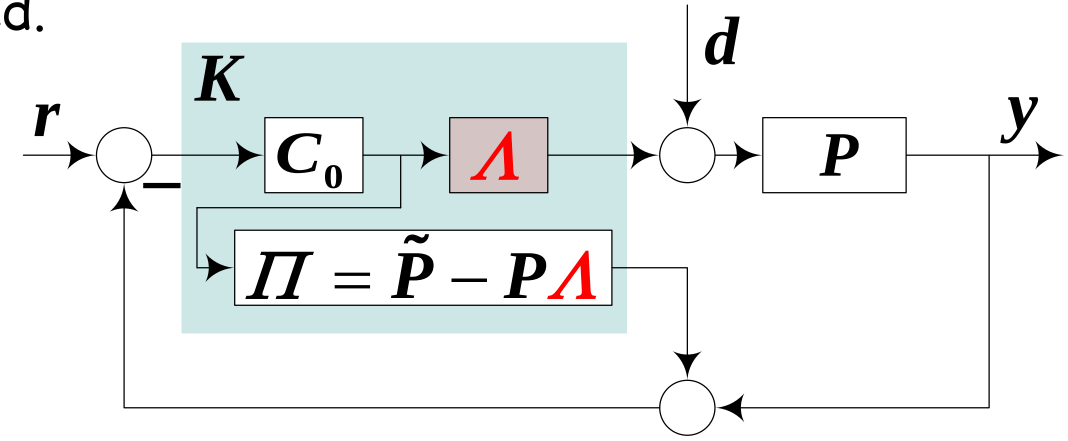
- State of the art – the GMDC of Jerome & Ray (1986)

✓ Based on the Dynamic Resilience Theory (DRT) that considers the DT decoupled response as the best achievable response (in the limit)

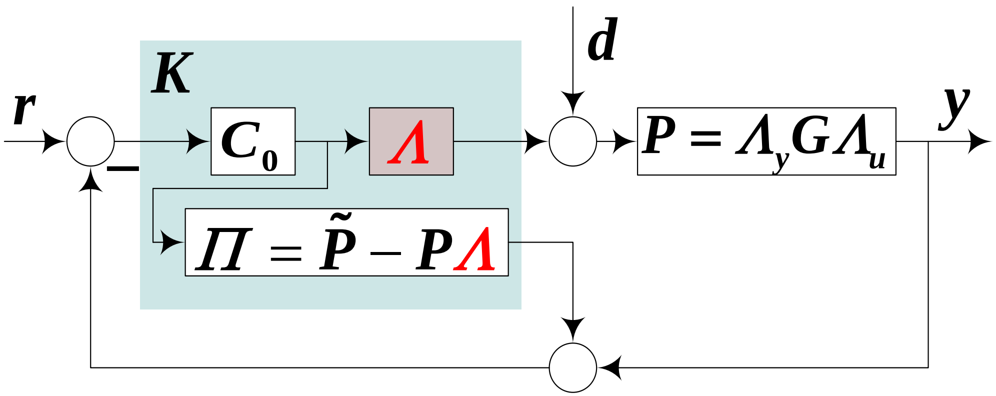
Λ - Matrix of artificially added delays if process fails the RT

C_0 - primary controller (typically a diagonal PI)

$\tilde{P}$ - is the process (P or $P\Lambda$)with the smallest delay in each row subtracted.



The GMDC for I/O DTs



G - rational TF matrix

Λ_u, Λ_y - diagonal delay I/O matrices

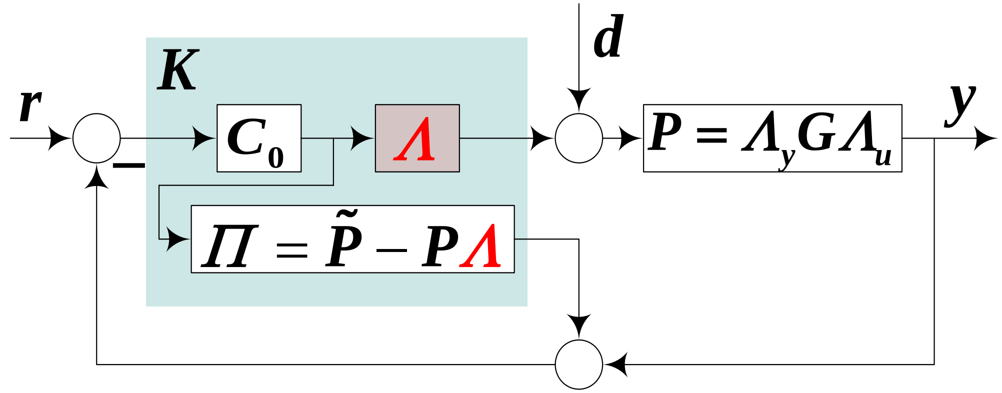
Π - predictor

K - overall GMDC

P passes the RT: $\tilde{P}\Lambda = (\Lambda_y \Lambda_u)^{-1} \Lambda_y G \Lambda_u$

P doesn't pass the RT: $\tilde{P} = (\Lambda_y \Lambda_u \Lambda)^{-1} \Lambda_y G \Lambda_u \Lambda$

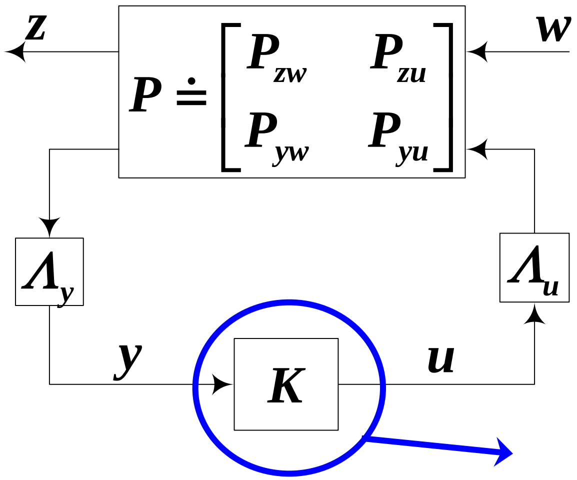
GMDC facts



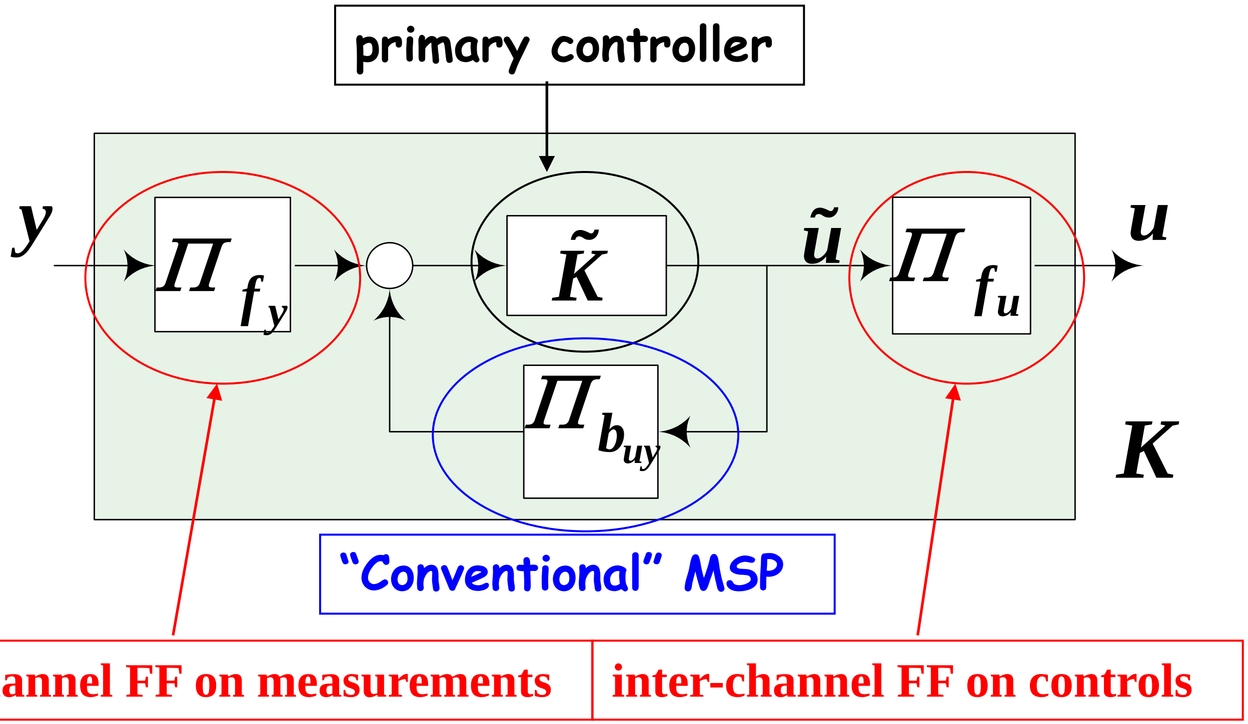
- $\tilde{P}$ may be irrational ⟶ delays not eliminated from the characteristic equation
- Not applicable to unstable processes!
- No design/tuning method for C_0 provided!

☺ Applicable to the more general distribution of DTs

FASP - structure



$$K = \Pi_{f_u} \tilde{K}(I - \Pi_{b_{uy}} \tilde{K})^{-1} \Pi_{f_y}$$



$$\Pi_{b_{uy}} = \tilde{P}_{yu} - \Pi_{f_y} \Lambda_y P_{yu} \Lambda_u \Pi_{f_u}$$

Role of FF compensators and predictor

- FF on control compensates for the coupling effects due to the longer delayed control channels on the outputs that are affected by the shorter delayed input channels.
- FF on measurement compensates for longer delayed measurements of exogenous inputs that are sensed through the shorter delayed channels.
- Predictor eliminates all DTs from the characteristic equation

✓ All three components consist of FIR blocks

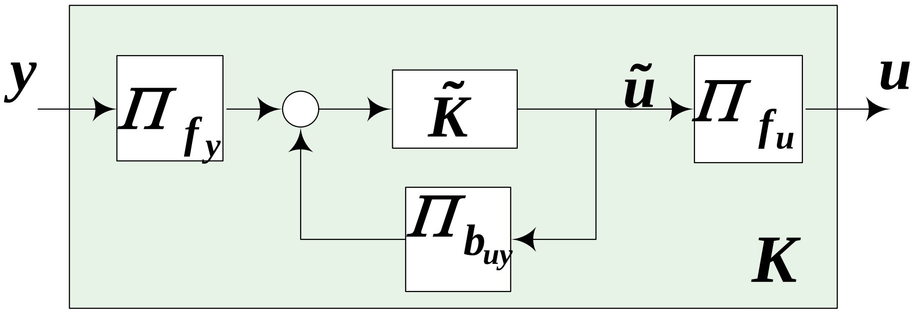
FASP facts

- All H^2 controllers are FASPs
  (Mirkin, Palmor & Shneiderman, 2009)
- FASP is intrinsic to all H^∞ controllers
  (Miensma & Mirkin, 2005)

} true extension of single delay MSP!

- Performance bounds of FASP are almost always better than those of GMDC.
  (Shneiderman, Palmor & Mirkin , 2009)
- FASP is performance dependent

FASP – potential implementation difficulties



- Numerical instabilities

- High dimensionality of rational components.

- Realization of FIR blocks

Numerical instabilities

- ☹ Both primary controller as well as predictor and FF compensators rely on matrix exponentials of Hamiltonian matrices → elements grow rapidly with large delays and render the implementation numerically unstable.
- ☺ It has been shown* that under mild conditions the overall H^2 controller can be realized with matrix exponentials of just Hurwitz matrices
- 😐 However, the above increases significantly the dimensions of the primary controller

*(Mirkin, Palmor & Shneiderman, 2009)

High dimensionality of rational components

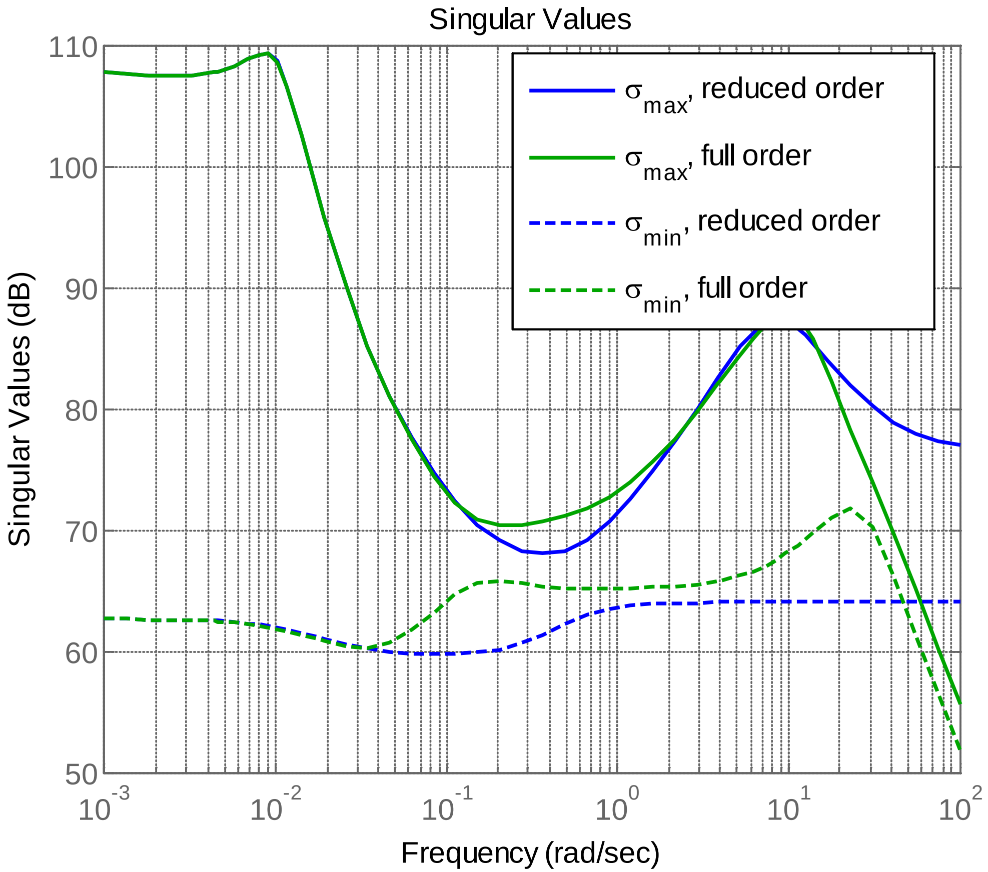
- Balanced truncation used to reduce dimensions of primary controllers simply and effectively. Criterion: similar singular values of full and reduced order primary controllers throughout bandwidth of optimal closed loop.

- Experience with the case study at hand shows that dimension reduction by at least a factor of 2 is possible with out affecting control performance significantly.

Example

Full order: 12
Reduced order: 6
Bandwidth: 1 rad/sec

Unstable pole left untouched!.



FASP - FIR blocks

- can be expressed as:

$$\Pi = \left[\begin{array}{c|c} A & B \\ \hline Ce^{-Ah} & 0 \end{array}\right] - \left[\begin{array}{c|c} A & B \\ \hline C & 0 \end{array}\right] e^{-sh} = C \cdot \left(\int_0^h e^{A(\theta-h)} e^{-\theta s} d\theta \right) \cdot B$$

- ✓ FIR (in $[0,h]$) - entire function- no poles
- ✓ Irrational

Realization of FIR blocks

- FIR block based upon stable system can be realized as a difference of two systems

$$\Pi_s = \left[\begin{array}{c|c} A & B \\ \hline Ce^{-Ah} & 0 \end{array}\right] - \left[\begin{array}{c|c} A & B \\ \hline C & 0 \end{array}\right] e^{-sh}$$

- FIR block based upon unstable system must be realized with no unstable poles

$$\Pi_u = C \cdot \left(\int_0^h e^{A(\theta-h)} e^{-\theta s} d\theta \right) \cdot B$$

➔approximations required

Approximations of Π_u

- Numerical integrations (Lumped delay approximation)

$$\Pi_u = C \cdot \left(\int_0^h e^{A(\theta - h)} e^{-\theta s} d\theta \right) \cdot B \approx \frac{1}{\tau s + 1} \sum_{i=0}^{n} \eta_i C (I + \tau A) e^{A(\frac{i}{n} - 1)h} B e^{-s\frac{h}{n}i}$$

n - number of devisions of DT

η_i - approximation dependent (rectangle rule, trapezoid...)

τ- time constant used to assure finite bandwidth of approximation*

*(Mirkin, 2004)

Approximations of Π_u

✓ Quality approximation measure (QAM)**

$$QAM = \left[\max_{\theta \in [0,h]} \frac{h^3}{12n^2} \frac{\bar{\sigma}\left(C(I + \tau A) e^{A(\theta - h)} A^2 B \right)}{\bar{\sigma}\left(\Pi(0) \right)} \right]^{-1}$$

➲ QAM large- safe to use LDA. If small increase n or use Pade approximation (PA)

** (German, 2011)

Approximations of Π_u

- PADE approximation (AP) to cancel all unstable poles

  - ✓ Delays in Π replaced by Pade approximation (of order n_p)
  - ✓ Zeros (z_i) generated cancel unstable poles (p_i) within a distance ε
  - ✓ Tradeoff between n_p and ε

Example 1 - large QAM (> 10^3)

DT: $h = 5[sec]$

LDA: $n = 10, \tau = 1[sec]$

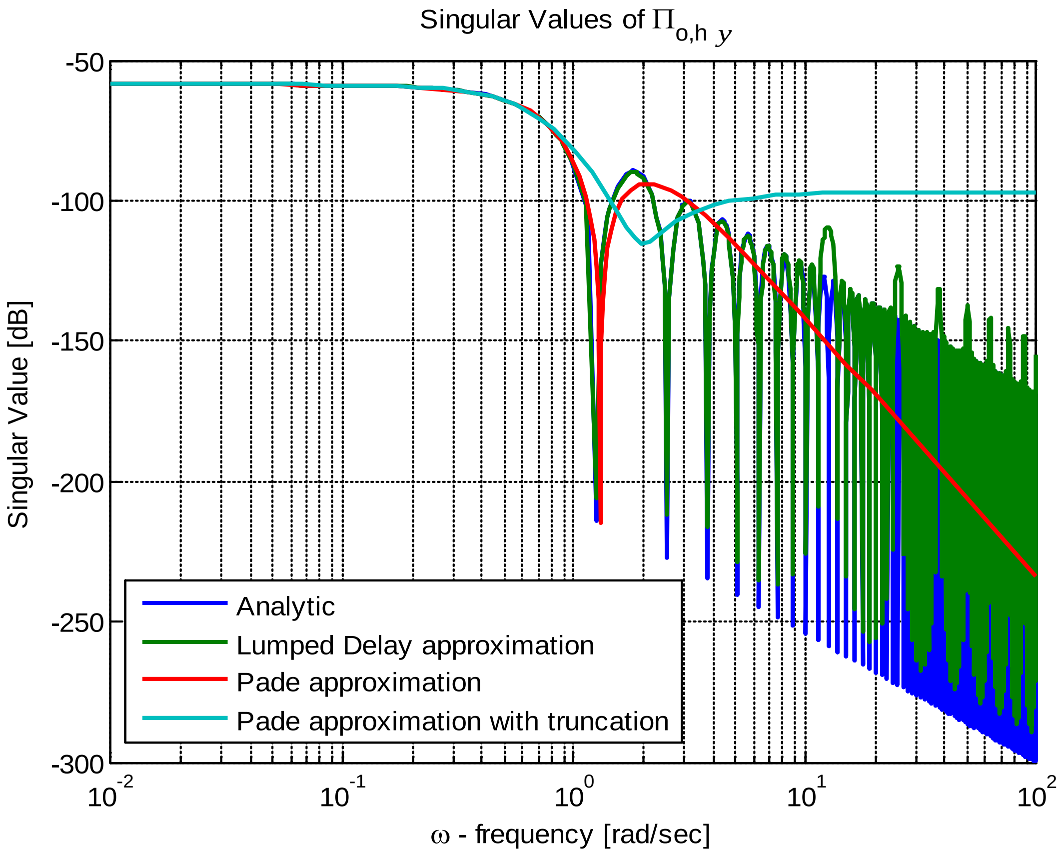
PA: $n_p = 4, \varepsilon = 10^{-2}$

Computation times:
Constant input for 10 sec with sampling of 0.01sec

$t_{lda} = 0.0223[sec]$

$t_{pa} = 0.051[sec]$

$t_{pa,truncated} = 0.0384[sec]$

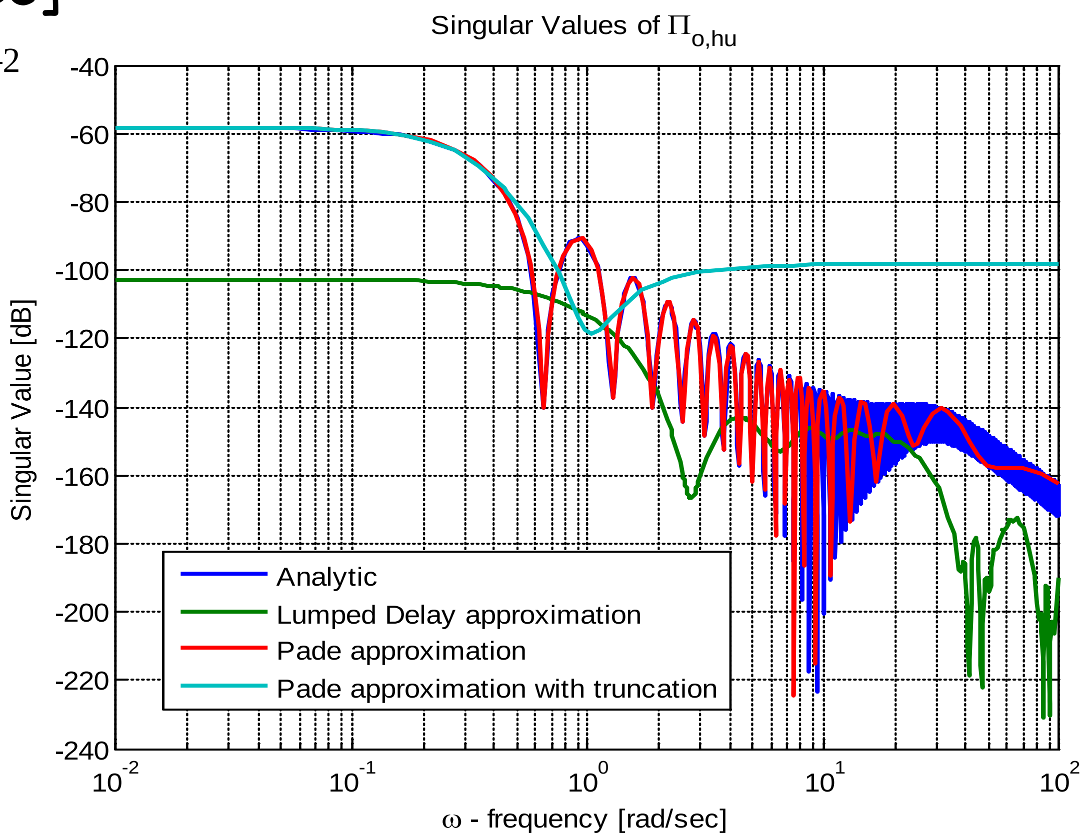


Example 2 - small QAM (□ 10^{-3})

DT: $h = 10[sec]$

LDA: $n = 70, \tau = 1[sec]$

PA: $n_p = 40, \varepsilon = 10^{-2}$



Computation times:
Constant input for 10 sec with sampling of 0.01sec

$t_{lda} = 0.0439[sec]$

$t_{pa} = 0.0597[sec]$

$t_{pa,truncated} = 0.0445[sec]$

The original quadruple-tank process (QTP)

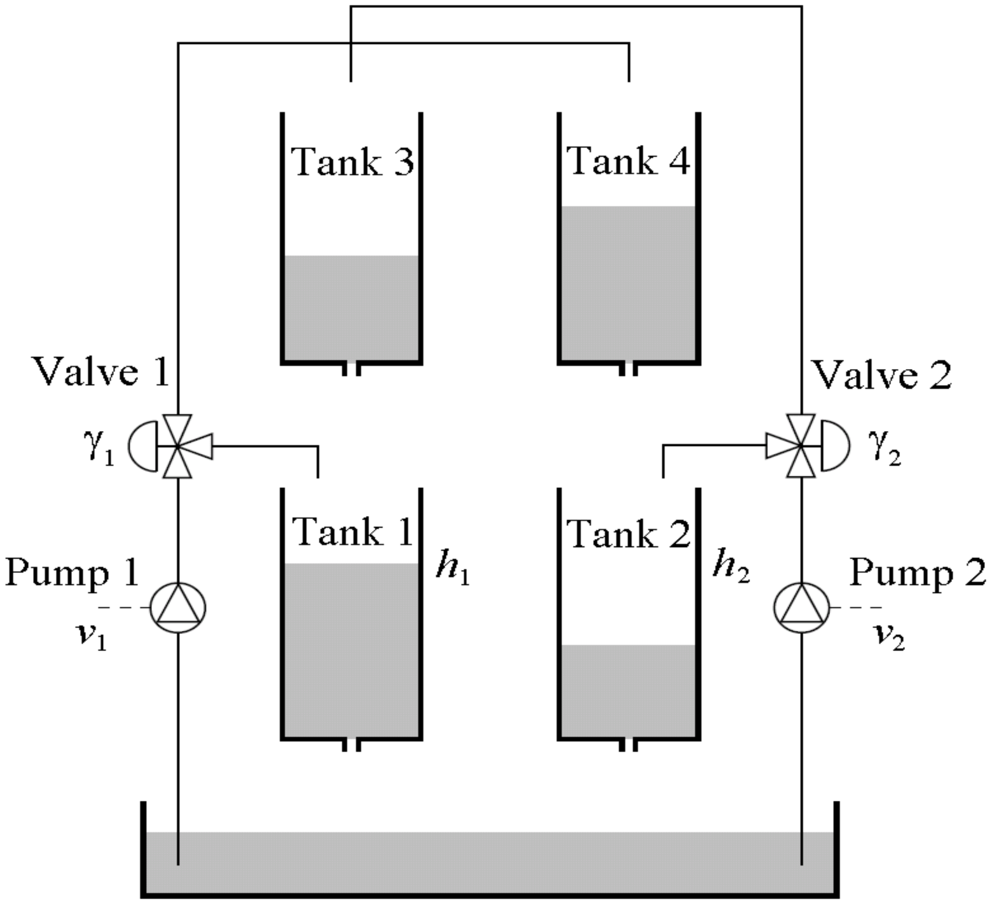
v_1, v_2 - voltages to pumps

$\gamma_1, \gamma_2 \in (0,1)$ - flow dividers

h_1, h_2 - outputs

NMP $\quad 0 < \gamma_1 + \gamma_2 < 1$

MP $\quad 1 < \gamma_1 + \gamma_2 < 2$



The quadruple-tank process with dead-times (QTPwDT)

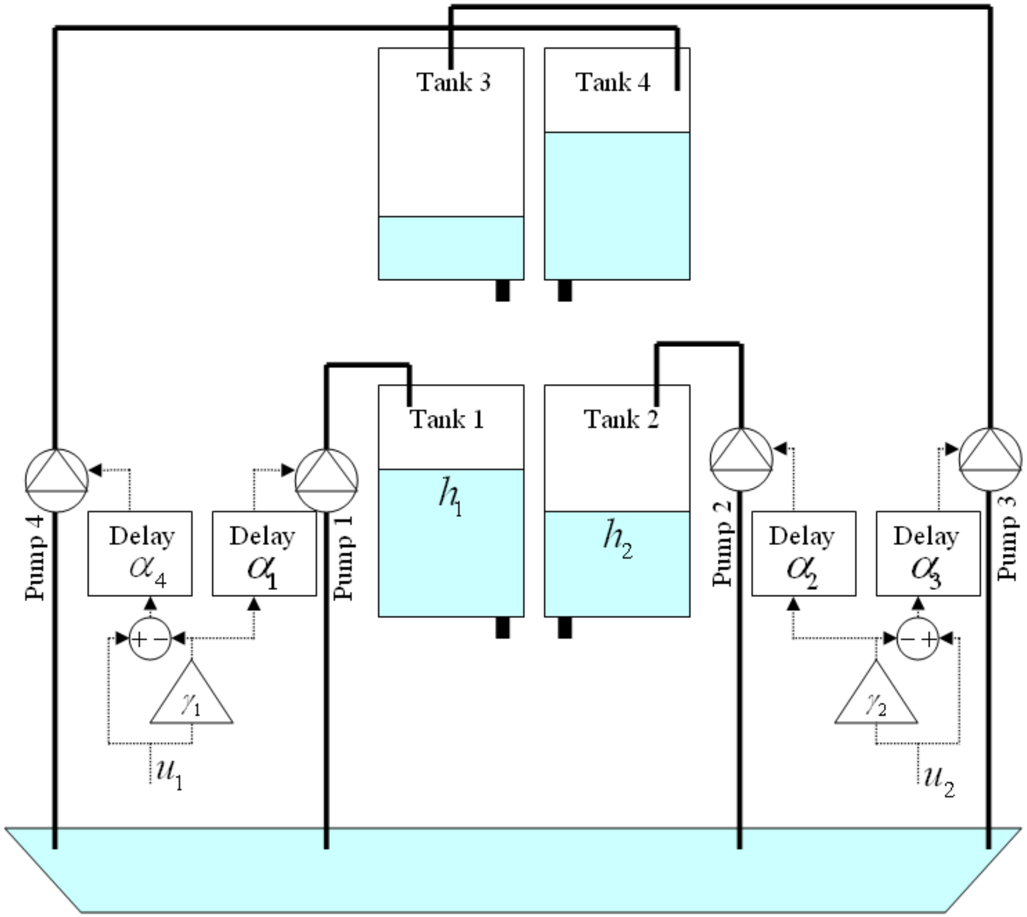
u_1, u_2 - voltages to pump

$\gamma_1, \gamma_2 \in (0,1)$ - flow dividers

h_1, h_2 - outputs

✓Linearized plant:

$$P(s) = \begin{bmatrix} P_{11}(s)e^{-s\alpha_1} & P_{12}(s)e^{-s\alpha_3} \\ P_{21}(s)e^{-s\alpha_4} & P_{22}(s)e^{-s\alpha_2} \end{bmatrix}$$



Properties of QTPwDT*

✓Depend on β and G(0) where

$$\beta \triangleq \alpha_1 + \alpha_2 - \alpha_3 - \alpha_4$$

$$G(s) \triangleq \frac{-K\cdot(1-\gamma_1)\cdot(1-\gamma_2)/(\gamma_1\gamma_2)}{(1+s\cdot T_3)\cdot(1+s\cdot T_4)}\cdot e^{s\cdot\beta}$$

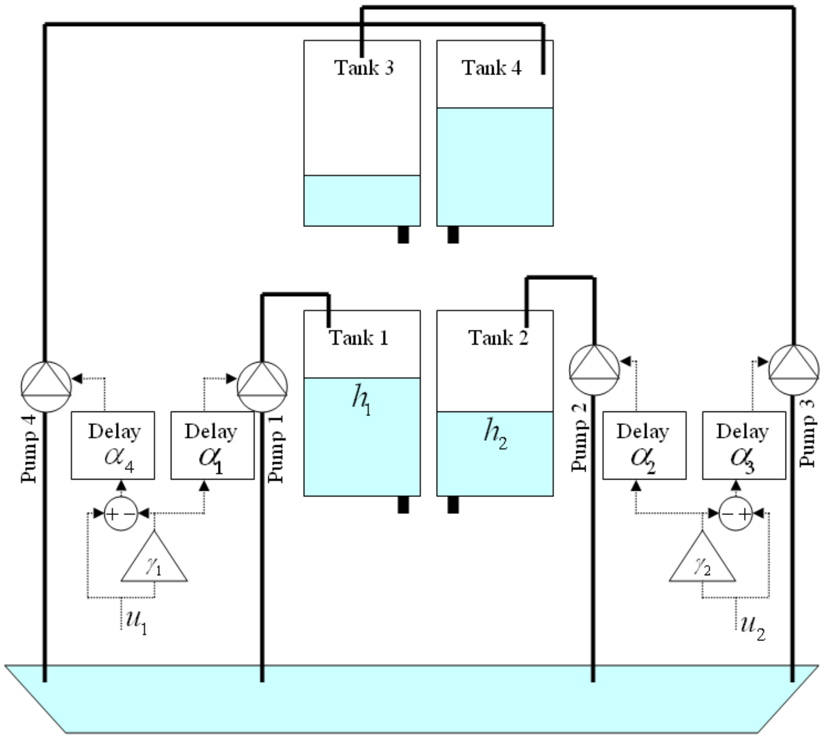
$$K \triangleq k_3 k_4/(k_1 k_2)$$

✓ if $\beta \le 0$ and $G(0) < 1$ - no NMP zeros

if $\beta \le 0$ and $G(0) > 1$ - at least one NMP zero

✓ if $\beta > 0$ - infinite NMP zeros

G(0) determines the behavier of the dominant NMP zeros



* (Shneiderman & Palmor, 2010)

Experimental set-up

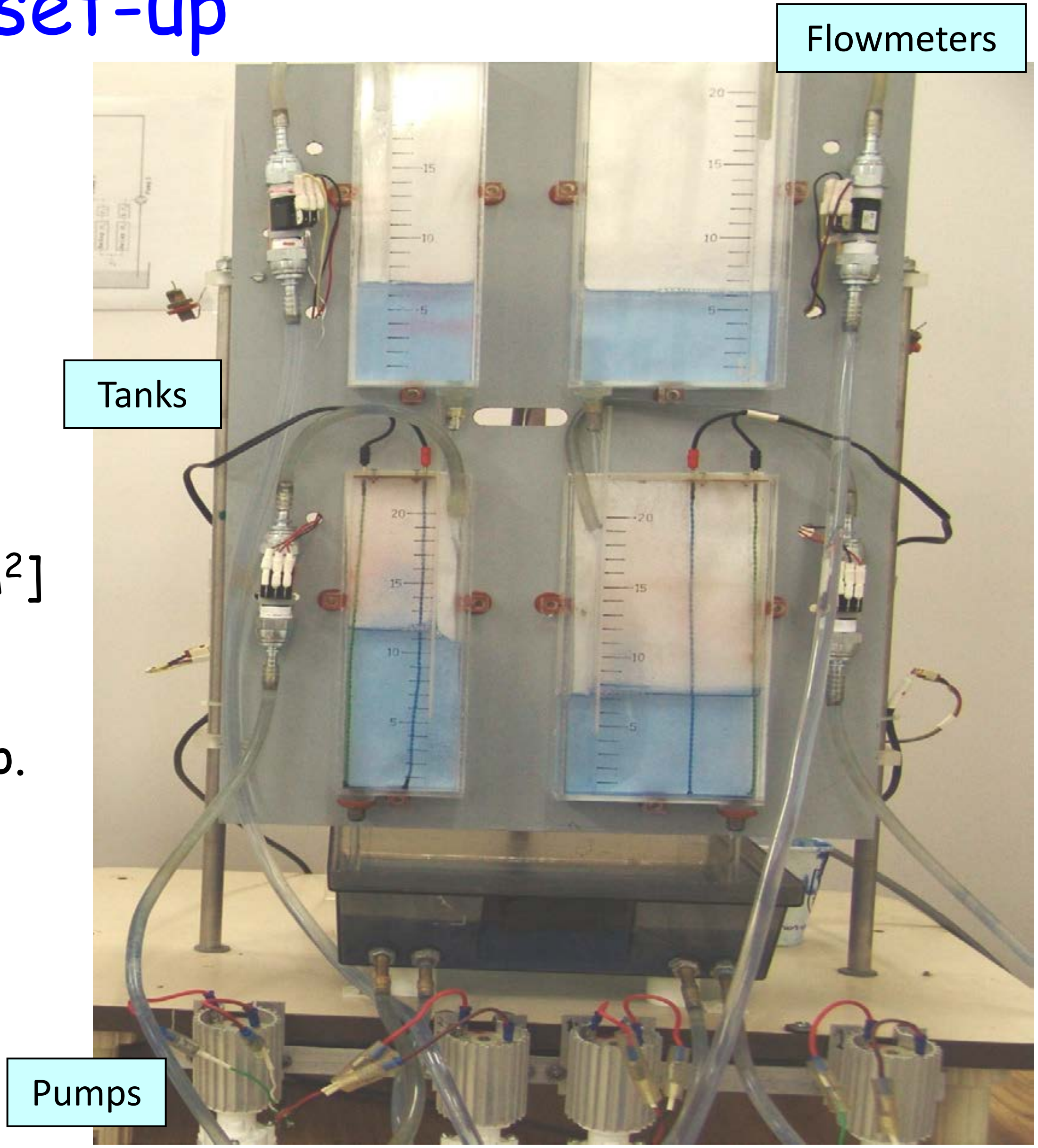
<u>Gear pumps:</u>

Capacity -2.3 [lit/min]
Voltage -3:12 [V]
Gain – k_i [$cm^3/(s.V)$]

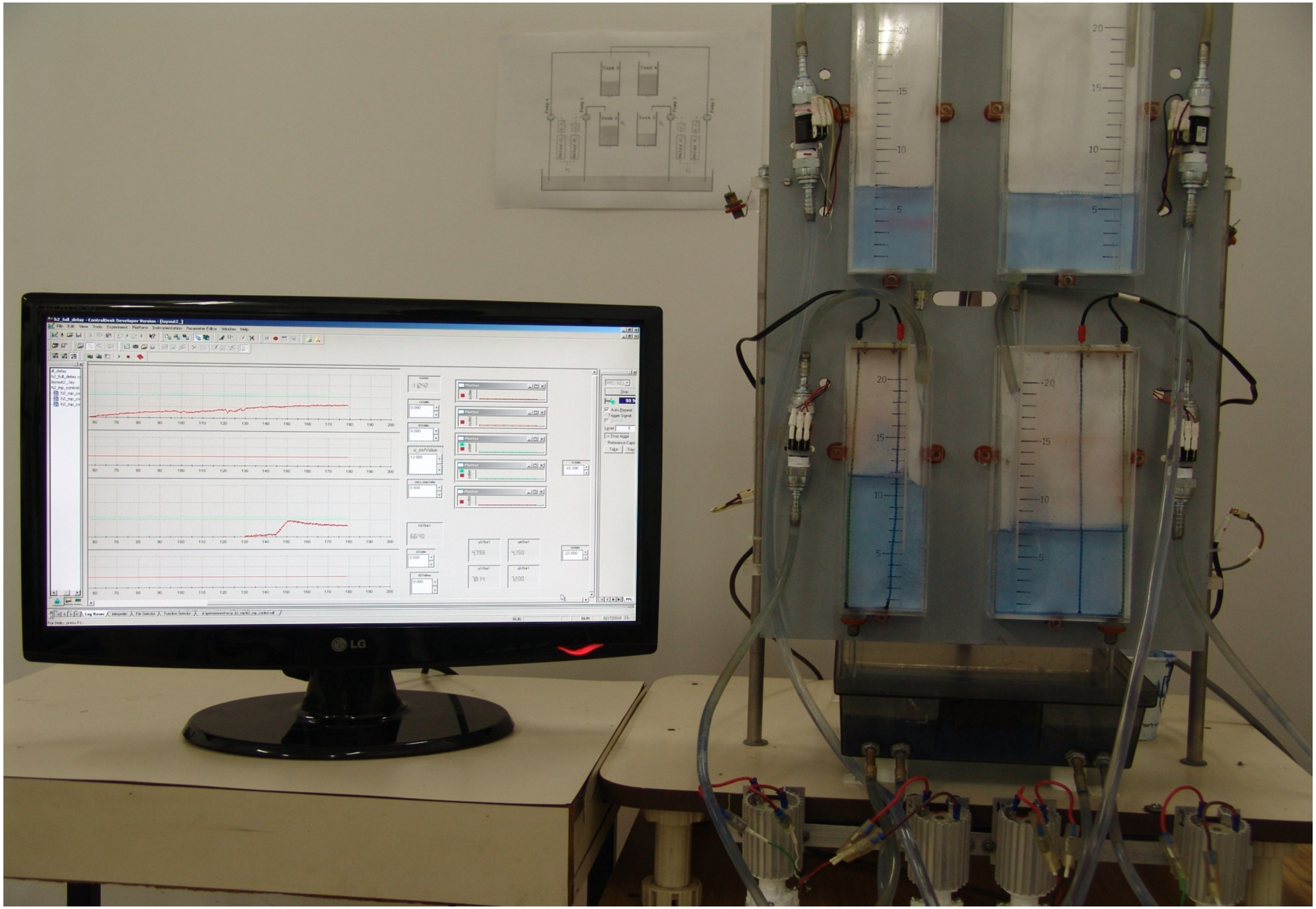
<u>Tanks</u>

Height – 23 [cm]
Cross section – A_i [cm^2]
Cross section outlet: a_i [cm^2]
γ_i - voltage deviders

Servo control on each pump.



Experimental set-up



Modeling and data

Linearized model:

$$P(s)=\begin{bmatrix} \dfrac{\gamma_1 T_1 k_1 / A_1 \cdot e^{-s\alpha_1}}{(1+sT_1)} & \dfrac{(1-\gamma_2)T_1 k_3 / A_1 \cdot e^{-s\alpha_3}}{(1+sT_3)(1+sT_1)} \\ \dfrac{(1-\gamma_1)T_2 k_4 / A_2 \cdot e^{-s\alpha_4}}{(1+sT_4)(1+sT_2)} & \dfrac{\gamma_2 T_2 k_2 / A_2 \cdot e^{-s\alpha_2}}{(1+sT_2)} \end{bmatrix}$$

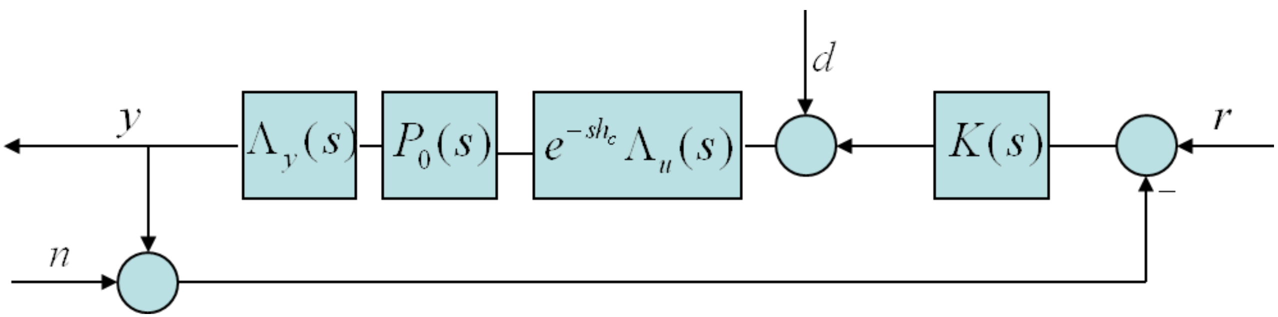
$$T_i=\frac{A_i}{a_i}\sqrt{\frac{2h_{i,ss}}{g}}$$

Parameter values of the laboratory QTPwDT.

i	A_i (cm^2)	a_i (cm^2)	k_i ($\mathrm{cm}^3/(\mathrm{s}\cdot\mathrm{V})$)	k_{i2} (cm^3/s)
1	12	0.26	3.808	2.712
2	20	0.26	3.831	2.006
3	12	0.21	3.904	3.069
4	20	0.21	3.752	3.499

Control Design

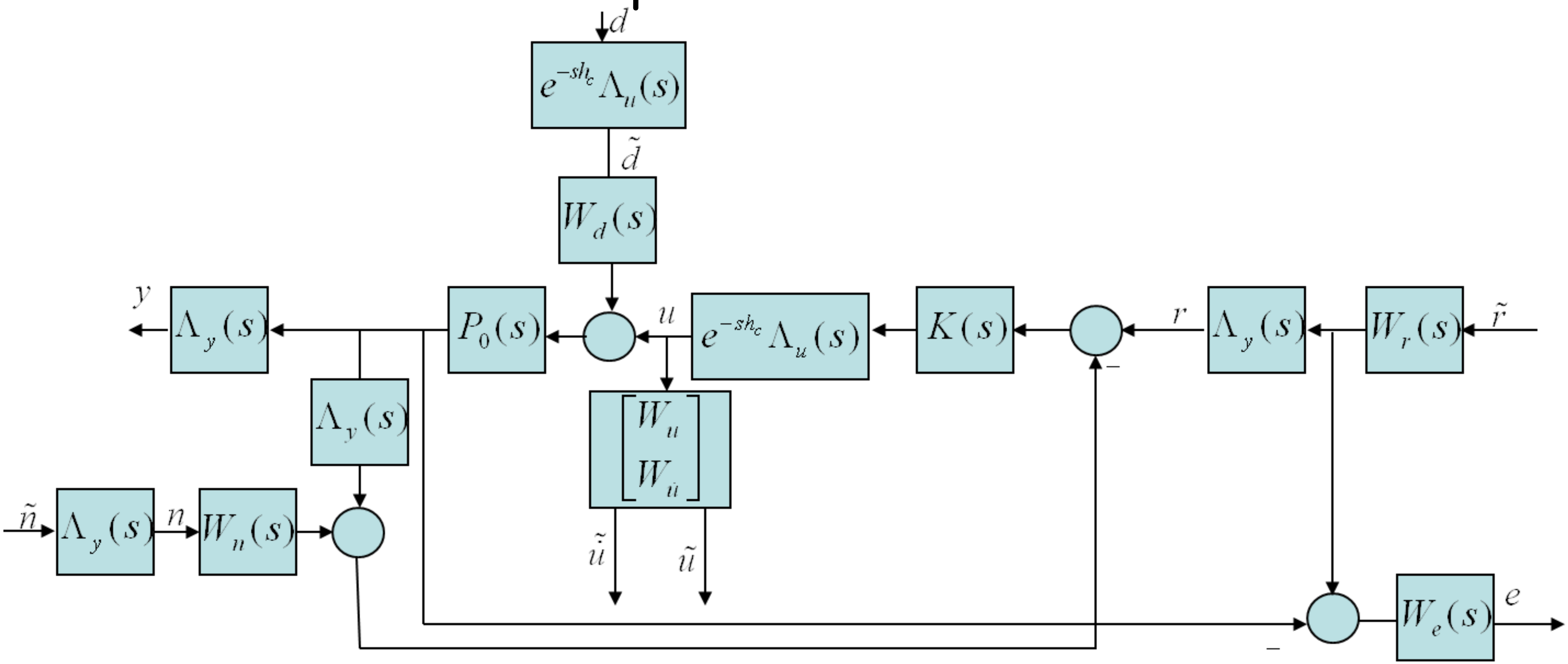
Standard configuration:



- ✓2x2 Process with adobe I/O delays + a common delay h_c
- ✓K(s) either FASP or GMDC
- ✓Controllers implemented via Simulink on dSPACE card

FASP -H^2 Design

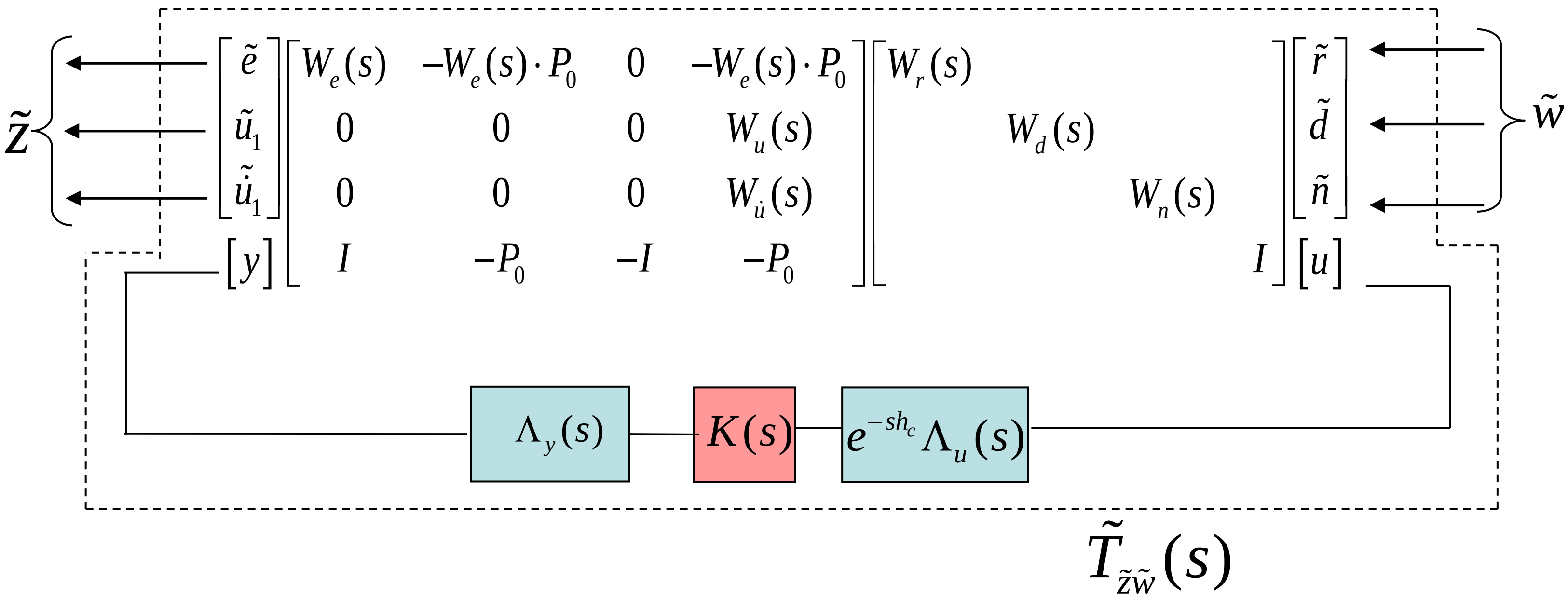
Generelized control problem:



weights added for performance and for guaranteeing solvability

FASP - H^2 Control Design

Generelized control problem:



Find internally stabilizing causal K(s) that minimizes $\left\| \tilde{T}_{\tilde{z}\tilde{w}} \right\|_2$

GMDC Design

Primary controller – a diagonal PI

tuned to have either similar closed-loop bandwidth or similar control effort as the corresponding FASP

Experimental cases

1) Cases with adobe I/O DTs + a common DT

   a. A MP case
   b. A NMP case

2) Cases with partial DT extraction

✓ Implementation of FASP:
- Primary controller truncated
- FF blocks approximated through PA
- Predictor blocks approximate via LDA

Experimntal results

Case 1a: MP case

$$\alpha_1 = 10,\ \alpha_2 = 25,\ \alpha_3 = 20,\ \alpha_4 = 15 \qquad \gamma_1 = 0.65,\ \gamma_2 = 0.6$$

$$h_c = 10,\ \Lambda_y = \begin{bmatrix} 1 & \\ & e^{-5s} \end{bmatrix}, \Lambda_u = \begin{bmatrix} 1 & \\ & e^{-10s} \end{bmatrix} \qquad \left.\begin{array}{l} \beta = 0 \\ |G(0)| = 0.294 \end{array}\right\}$$

Fasp:

$$W_r(s) = W_d(s) = \frac{1}{s+0.0005}; W_e(s) = 12000 \begin{bmatrix} \frac{10}{s+10} & 0 \\ 0 & \frac{1}{s+1} \end{bmatrix};$$

$$W_n(s) = 8; W_u(s) = 0.001; W_{\dot{u}}(s) = \frac{s}{0.005s+1}$$

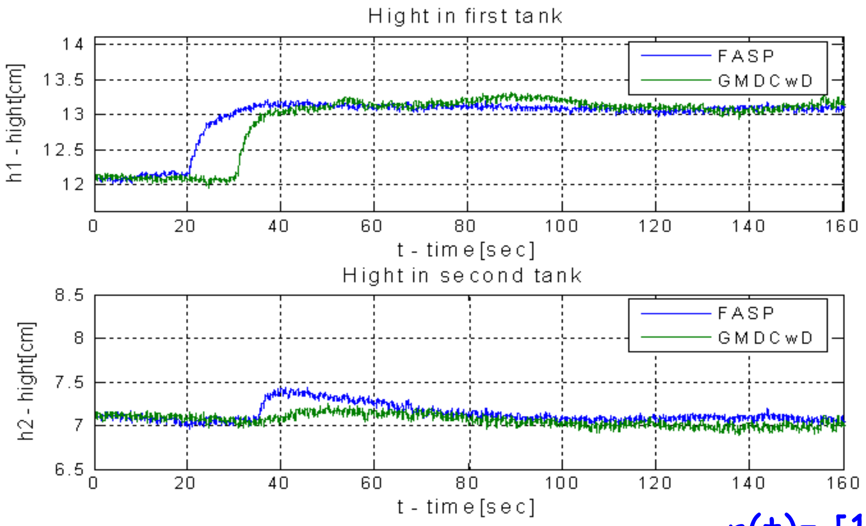
GMDC:

$$D = \begin{bmatrix} e^{-10s} & \\ & 1 \end{bmatrix}$$

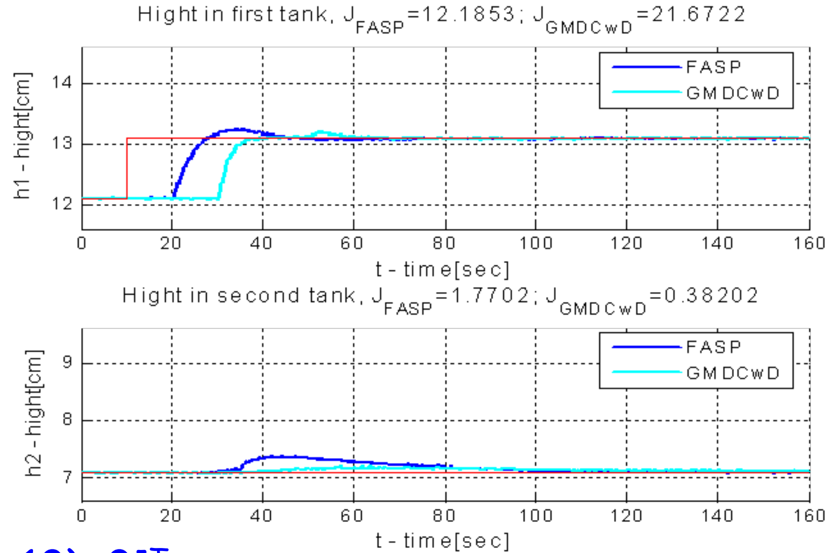
Case 1a - servo

Responses to Step Change in References

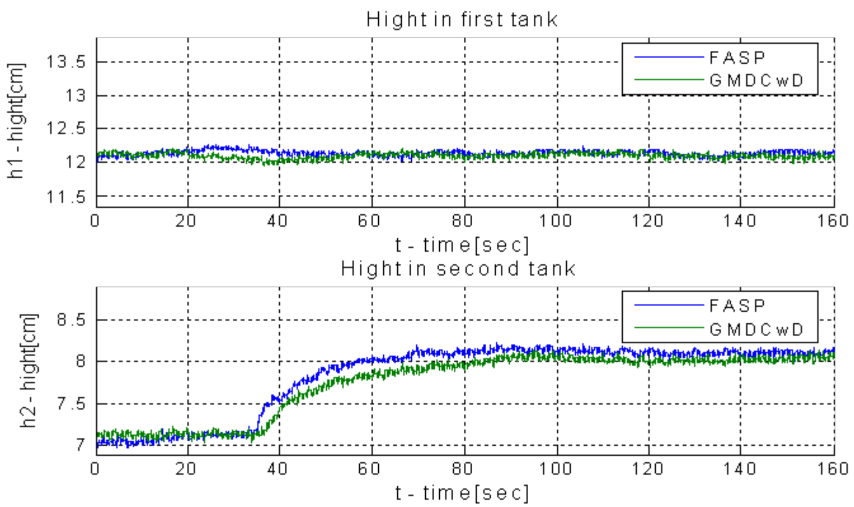
Experiment

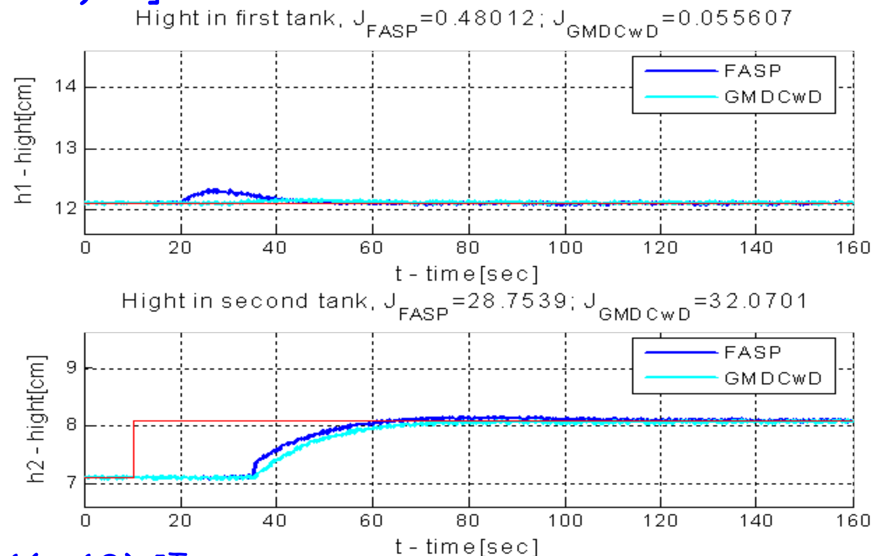


Simulation



$r(t)= [1(t-10) \;\; 0]^T$

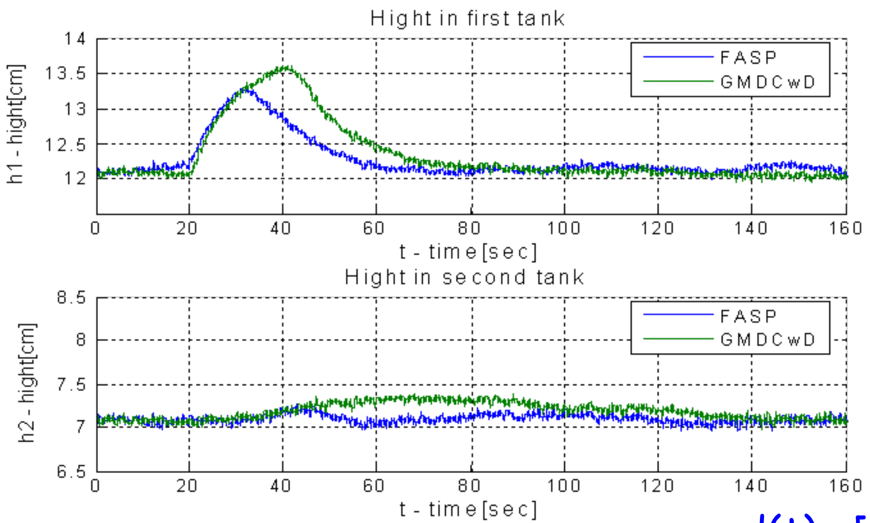


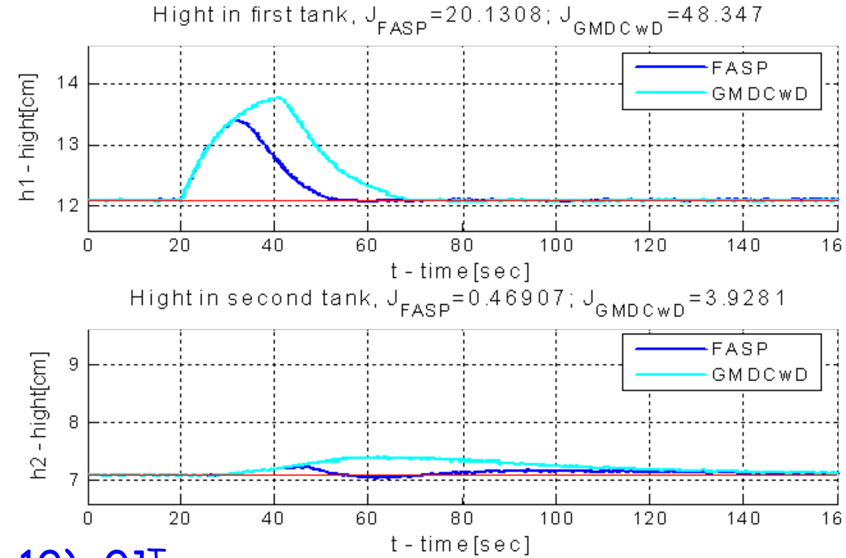


$r(t)= [0 \;\; 1(t-10)]^T$

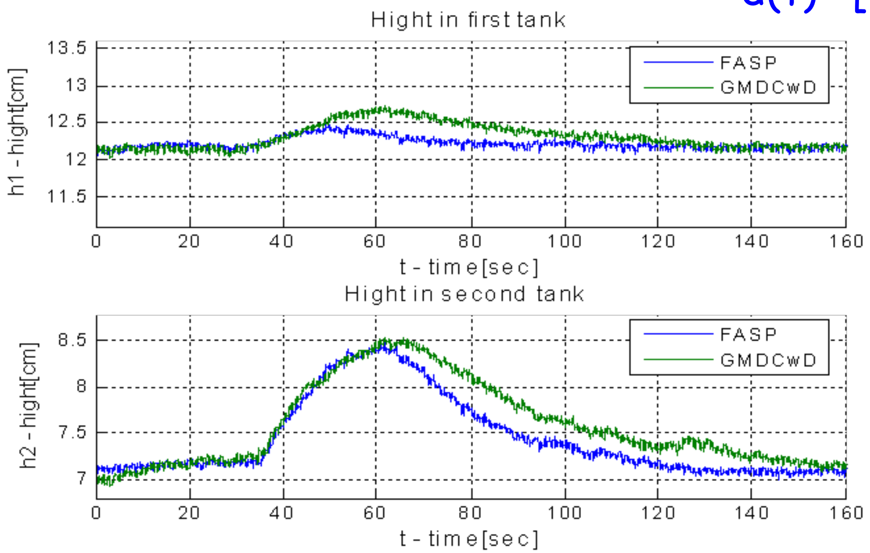
Case 1a - Disturbance attenuation

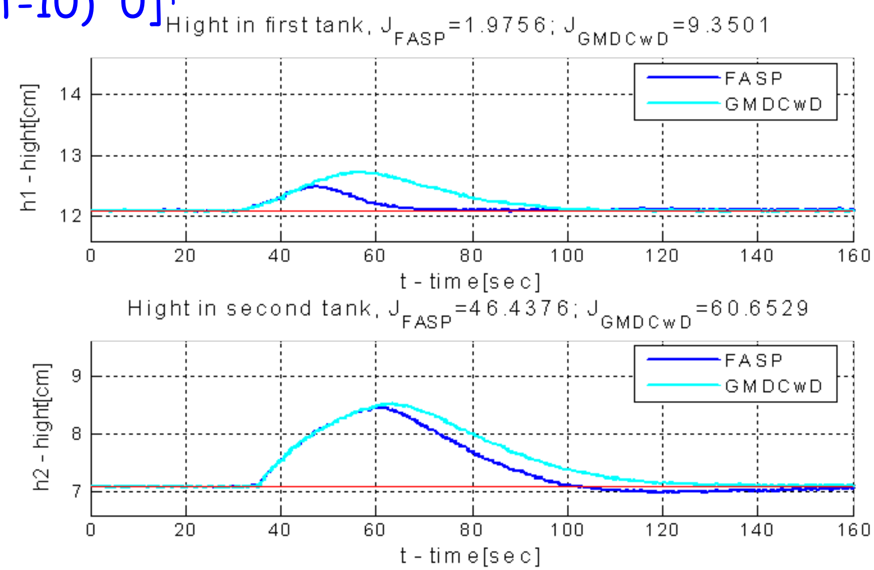
Experiment | Simulation





$d(t)= [1(t-10)\ \ 0]^T$





$d(t)= [0\ \ 1(t-10)\ ]^T$

Experimntal results

Case 1b: NMP case

$$\alpha_1 = 10,\ \alpha_2 = 25,\ \alpha_3 = 20,\ \alpha_4 = 15 \qquad \gamma_1 = 0.4,\ \gamma_2 = 0.35$$

$$h_c = 10,\ \Lambda_y = \begin{bmatrix} 1 & \\ & e^{-5s} \end{bmatrix}, \Lambda_u = \begin{bmatrix} 1 & \\ & e^{-10s} \end{bmatrix} \qquad \left.\begin{matrix} \beta = 0 \\ |G(0)| = 2.633 \end{matrix}\right\}$$

Fasp:

$$W_r(s) = W_d(s) = \frac{1}{s+0.0005}; W_e(s) = \frac{20}{s+1}; W_n(s) = 7.5;$$

$$W_u(s) = 0.001; W_{\dot{u}}(s) = \frac{s}{0.005s+1}$$

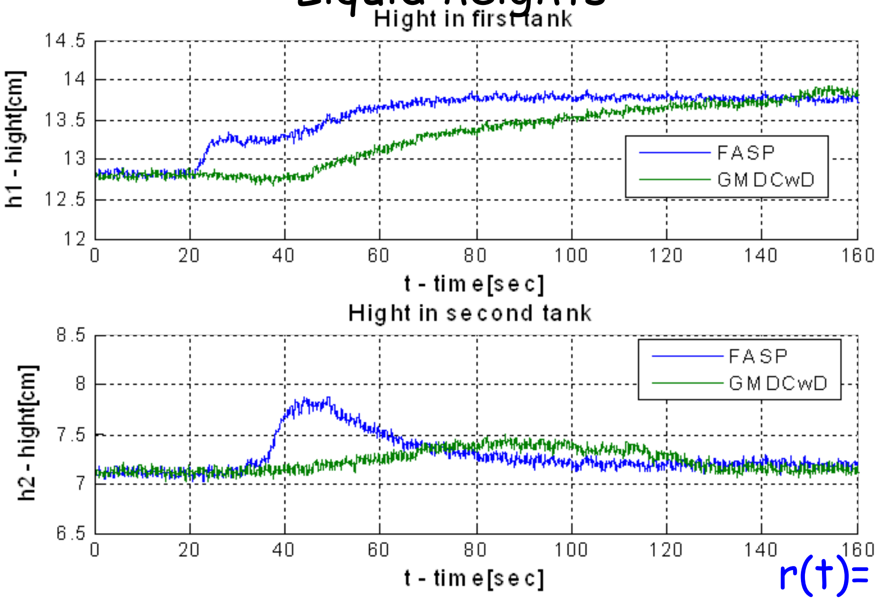
GMDC:

$$D = \begin{bmatrix} e^{-10s} & \\ & 1 \end{bmatrix}$$

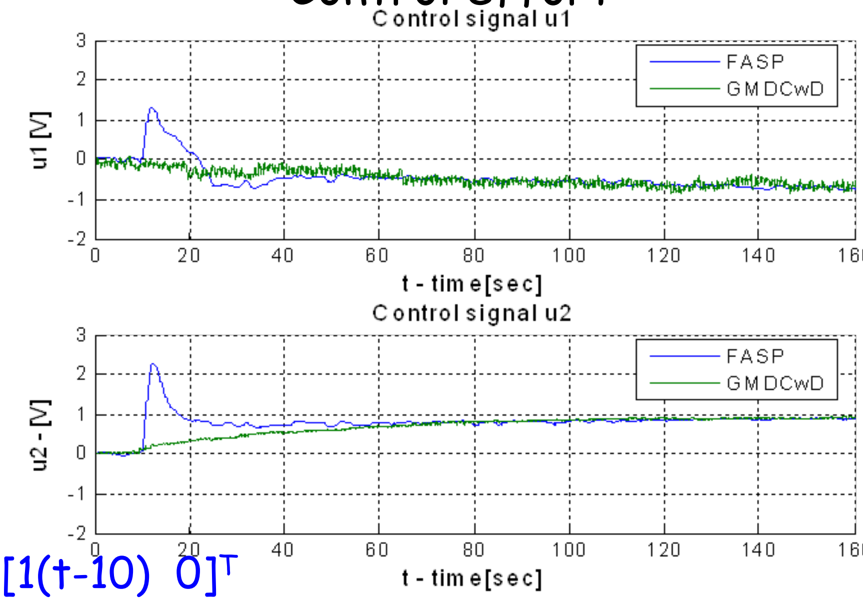
Case 1b - servo

Responses to Step Change in References

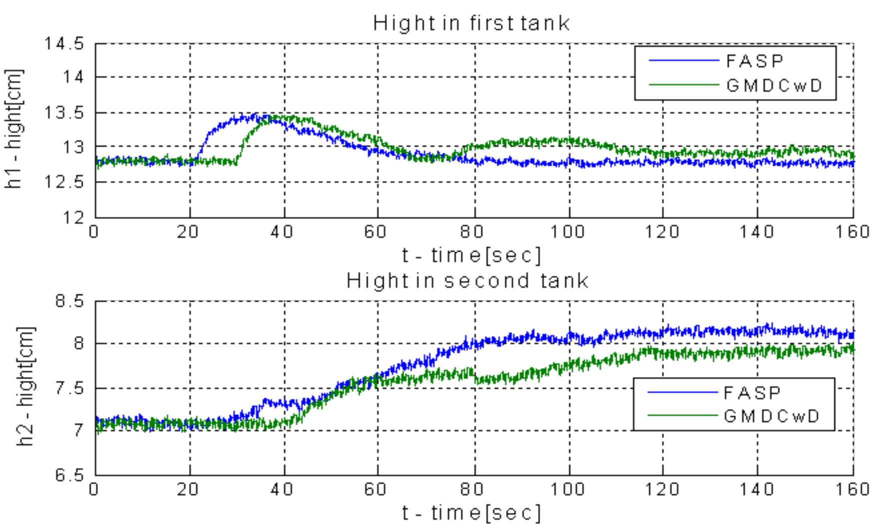
Liquid heights

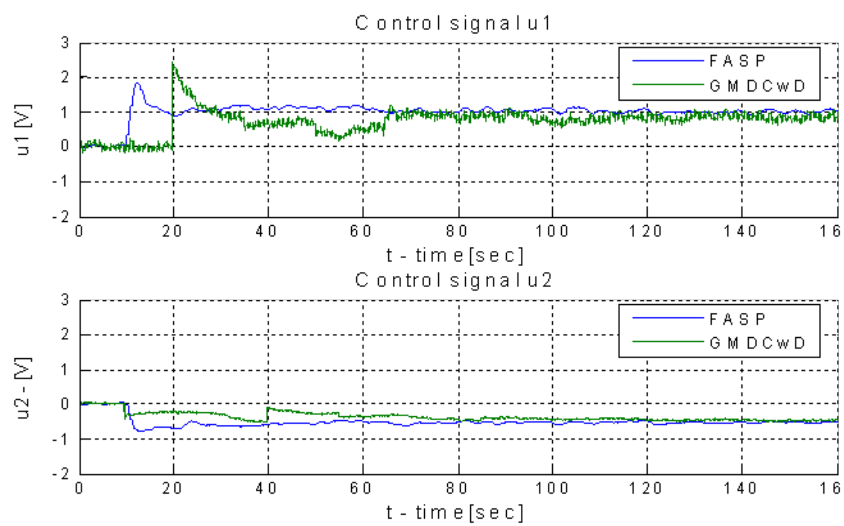


Control effort



$r(t) = [1(t-10)\ \ 0]^T$



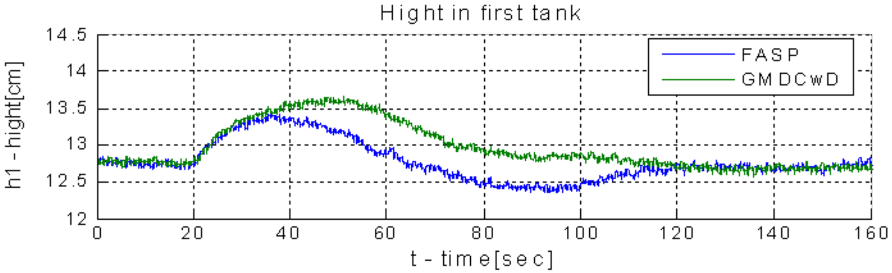


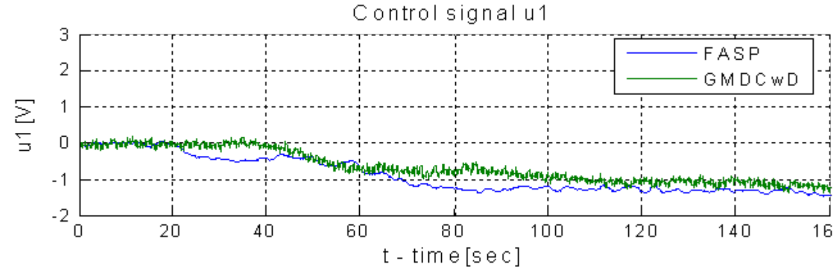
$r(t) = [0\ \ 1(t-10)\ ]^T$

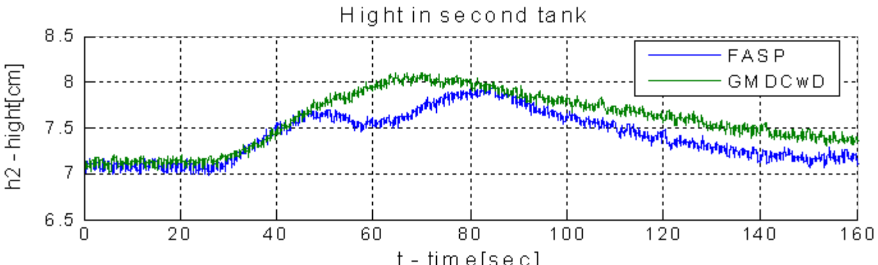
Case 1b - Disturbance attenuation

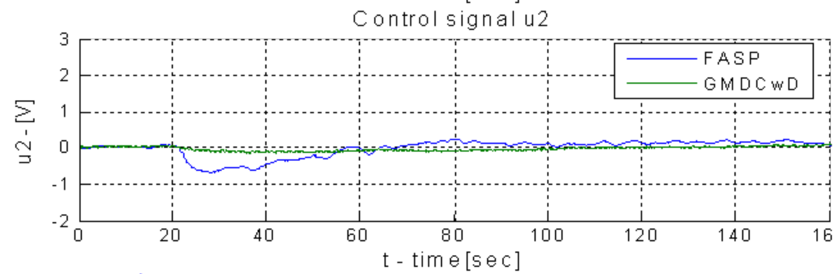
Liquid heights

Control effort

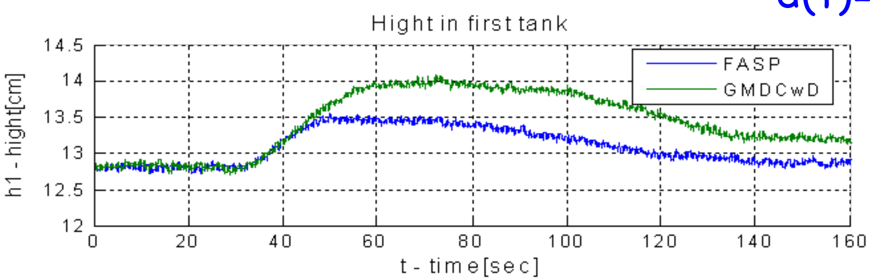


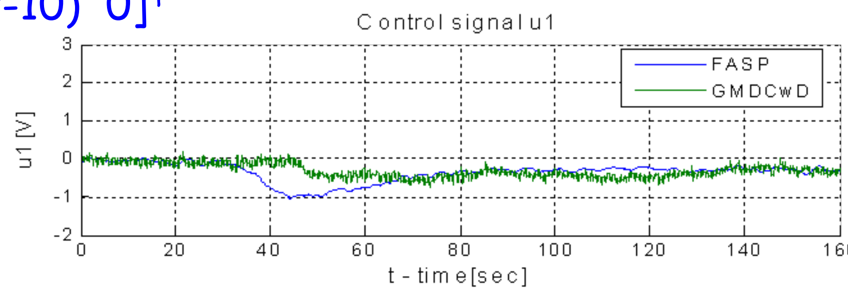


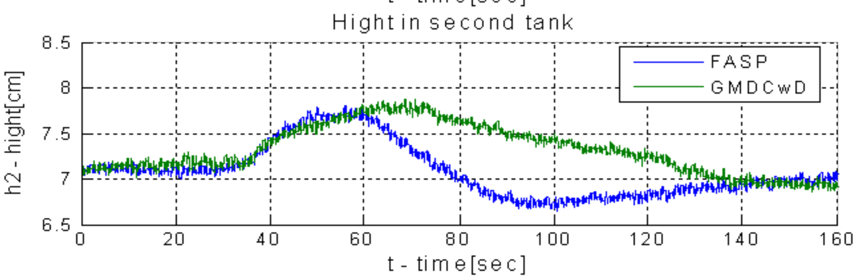


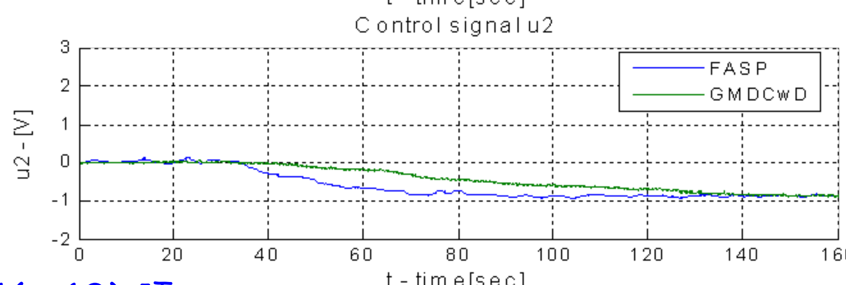


$d(t) = [1(t-10) \;\; 0]^T$









$d(t) = [0 \;\; 1(t-10)\,]^T$

Experimental results

2) 5 MP and 5 NMP Cases with full/partial DT extraction

$$1-\begin{bmatrix}10 & 20\\15 & 25\end{bmatrix}\Rightarrow \Lambda_u=\begin{bmatrix}0 & \\ & 10\end{bmatrix},\Lambda_y=\begin{bmatrix}0 & \\ & 5\end{bmatrix},h_c=10 \qquad \eta=0 \qquad \Rightarrow D=\begin{bmatrix}10 & \\ & 0\end{bmatrix}$$

$$2-\begin{bmatrix}10 & 14\\18 & 12\end{bmatrix}\Rightarrow \Lambda_u=\begin{bmatrix}0 & \\ & 1\end{bmatrix},\ \Lambda_y=\begin{bmatrix}0 & \\ & 1\end{bmatrix},h_c=10, \qquad \eta=\begin{bmatrix}0 & 3\\7 & 0\end{bmatrix} \qquad \Rightarrow D=\begin{bmatrix}0 & \\ & 0\end{bmatrix}$$

$$3-\begin{bmatrix}10 & 18\\22 & 20\end{bmatrix}\Rightarrow \Lambda_u=\begin{bmatrix}0 & \\ & 5\end{bmatrix},\Lambda_y=\begin{bmatrix}0 & \\ & 5\end{bmatrix},h_c=10, \qquad \eta=\begin{bmatrix}0 & 3\\7 & 0\end{bmatrix} \qquad \Rightarrow D=\begin{bmatrix}0 & \\ & 0\end{bmatrix}$$

$$4-\begin{bmatrix}10 & 22\\18 & 20\end{bmatrix}\Rightarrow \Lambda_u=\begin{bmatrix}0 & \\ & 5\end{bmatrix},\Lambda_y=\begin{bmatrix}0 & \\ & 5\end{bmatrix},h_c=10, \qquad \eta=\begin{bmatrix}0 & 7\\3 & 0\end{bmatrix} \qquad \Rightarrow D=\begin{bmatrix}2 & \\ & 0\end{bmatrix}$$

$$5-\begin{bmatrix}5 & 17\\13 & 20\end{bmatrix}\Rightarrow \Lambda_u=\begin{bmatrix}0 & \\ & 9.5\end{bmatrix},\Lambda_y=\begin{bmatrix}0 & \\ & 5.5\end{bmatrix},h_c=5, \quad \eta=\begin{bmatrix}0 & 2.5\\2.5 & 0\end{bmatrix}\Rightarrow D=\begin{bmatrix}7 & \\ & 0\end{bmatrix}$$

Experimental results - MP cases

DT distrib-ution	Extraction (full/partial)	Similar BW or Control effort	Overall ISE for step in $r(t)$				Overall ISE for step in $d(t)$			
			$r(t)=\begin{bmatrix}1(t-10)\\0\end{bmatrix}$		$r(t)=\begin{bmatrix}0\\1(t-10)\end{bmatrix}$		$d(t)=\begin{bmatrix}1(t-10)\\0\end{bmatrix}$		$d(t)=\begin{bmatrix}0\\1(t-10)\end{bmatrix}$	
			FASP	GMDC	FASP	GMDC	FASP	GMDC	FASP	GMDC
$1-\begin{bmatrix}10 & 20\\15 & 25\end{bmatrix}$	Full	BW	**13.36**	22.07	**29.52**	32.14	**19.36**	52.3	**49.51**	70.01
$2-\begin{bmatrix}10 & 14\\18 & 12\end{bmatrix}$	Partial	BW	11.85	**11.56**	14.65	**13.83**	**18.67**	19.83	**17.05**	17.31
$3-\begin{bmatrix}10 & 18\\22 & 20\end{bmatrix}$	Partial	Control	12.22	**11.58**	**22.63**	22.77	**18.64**	21.44	**32.27**	37.06
$4-\begin{bmatrix}10 & 22\\18 & 20\end{bmatrix}$	Partial	Control	**12.85**	13.41	23.34	**22.91**	**20.33**	25.83	**32.78**	38.59
$5-\begin{bmatrix}5 & 17\\13 & 20\end{bmatrix}$	Partial	Control	**7.82**	13.95	**23.63**	28.66	**6.69**	25.68	**33.68**	55.88

Experimental results - NMP cases

DT distri-ution	Extraction (full/ partial)	Similar BW or Control effort	Overall ISE for step in $r(t)$				Overall ISE for step in $d(t)$			
			$r(t)=\begin{bmatrix}1(t-10)\\0\end{bmatrix}$		$r(t)=\begin{bmatrix}0\\1(t-10)\end{bmatrix}$		$d(t)=\begin{bmatrix}1(t-10)\\0\end{bmatrix}$		$d(t)=\begin{bmatrix}0\\1(t-10)\end{bmatrix}$	
			FASP	GMDC	FASP	GMDC	FASP	GMDC	FASP	GMDC
$1-\begin{bmatrix}10 & 20\\15 & 25\end{bmatrix}$	Full	BW	**41.04**	66.16	**50**	60.89	**34.42**	85.76	**37.8**	112.8
$2-\begin{bmatrix}10 & 14\\18 & 12\end{bmatrix}$	Partial	Control	**42.19**	52.9	**60.3**	68	**45.02**	71.84	**34.91**	55.98
$3-\begin{bmatrix}10 & 18\\22 & 20\end{bmatrix}$	Partial	BW	**45.31**	61.65	**66.47**	73.82	**48.25**	85.38	**42.21**	73.19
$4-\begin{bmatrix}10 & 22\\18 & 20\end{bmatrix}$	Partial	BW	**54.65**	90.61	**64.71**	71.47	**48.26**	86.48	**53.87**	112.36
$5-\begin{bmatrix}5 & 17\\13 & 20\end{bmatrix}$	Partial	BW	**42.36**	89.41	**52.9**	70.52	**31.57**	81.22	**31.36**	110.89

Summary and Conclusions

- ✓ The FASP controller has been designed , implemented and applied to a laboratory QTPwDT setup.

- ✓ The study demonstrates:
  - ✓ FASP implementation is feasible
  - ✓ FASP's rational primary controller may be truncated significantly with out performance degradation.
  - ✓ FIR blocks may be approximated either via the LDA or via PADE approximation. The QAM defined.
  - ✓ FASP outperforms GMDC in both setpoint tracking and disturbance rejection. Holds even in the more general DTs cases particularly for disturbance rejection.

Thank you for your attention!