Sammenligning av lineære og ulineære metoder for robust Anti-slug regulering

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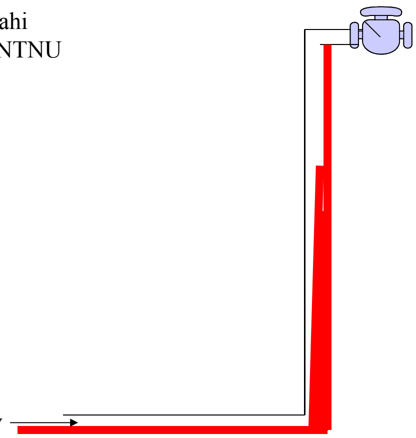
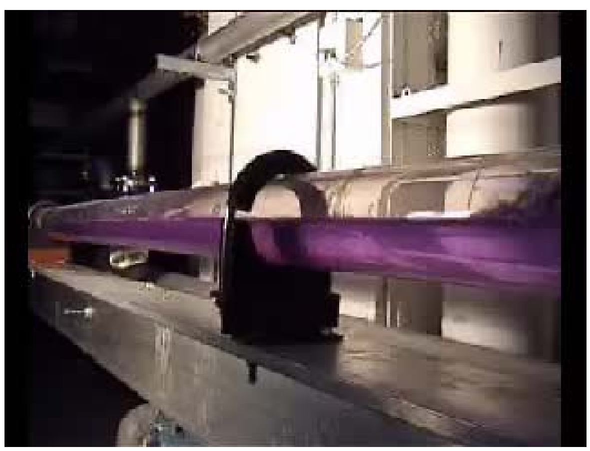


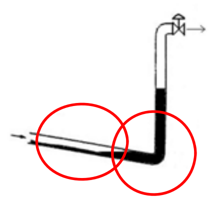
Two-phase pipe flow
(liquid and vapor)

Slug (liquid) buildup

Slug cycle (stable limit cycle)



Experiments performed by the Multiphase Laboratory, NTNU



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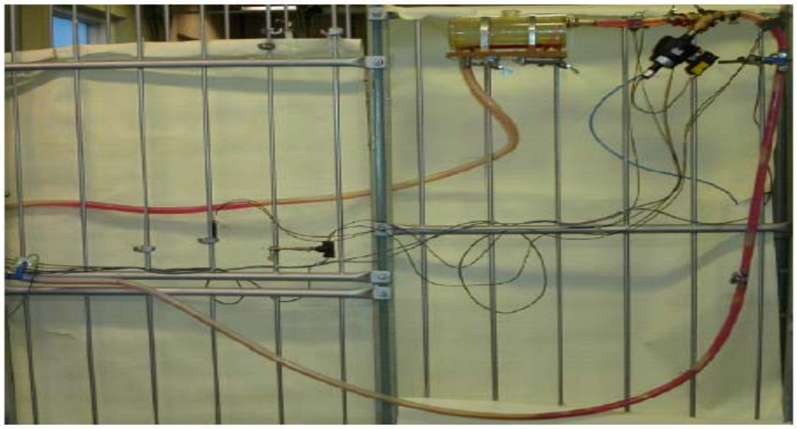
Experimental mini-loop (2003)



3

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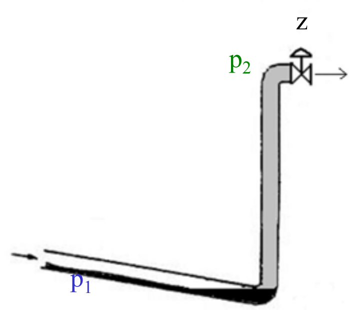
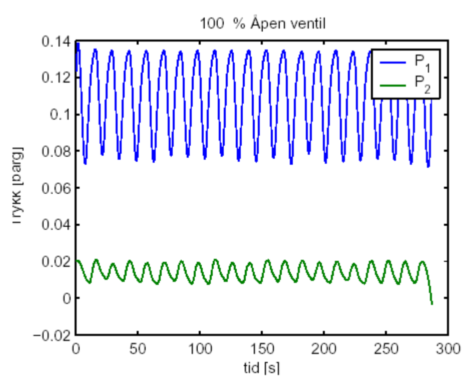
Experimental mini-loop
Valve opening (z) = 100%

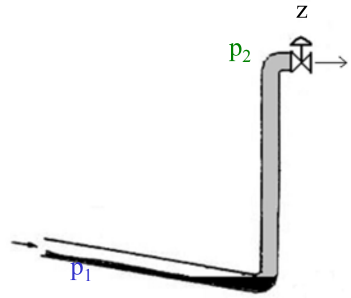


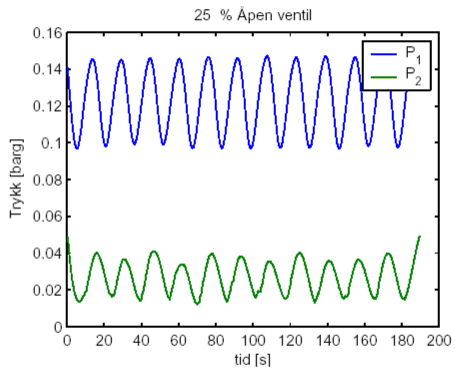


SLUGGING

4

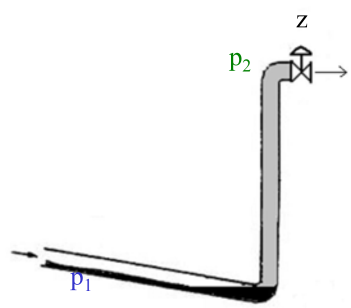
Experimental mini-loop
Valve opening (z) = 25%

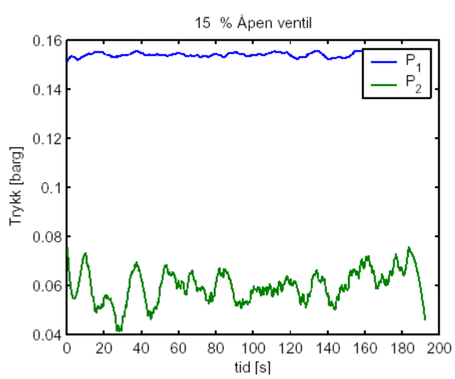




SLUGGING

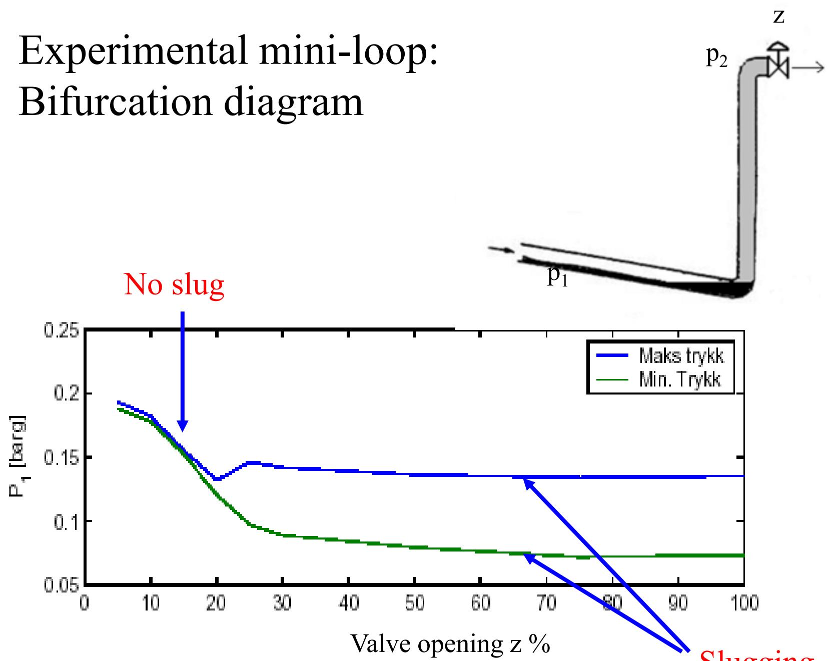
Experimental mini-loop
Valve opening (z) = 15%





NO SLUG

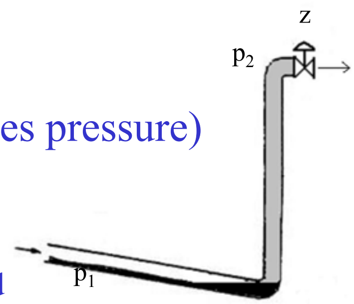
Experimental mini-loop: Bifurcation diagram



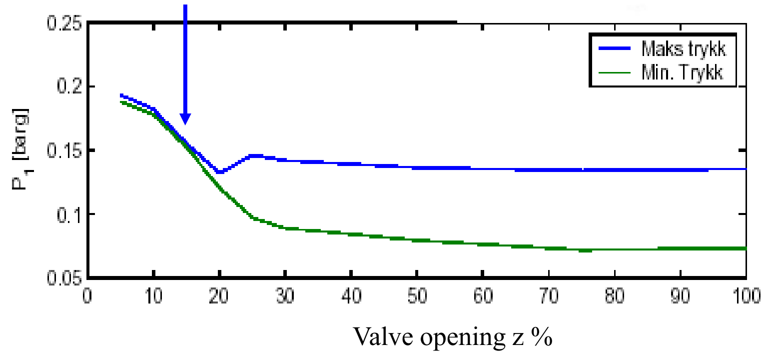
How to avoid slugging?

Design change

Avoid slugging:
1. Close valve (but increases pressure)



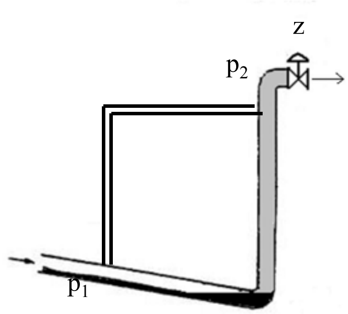
No slugging when valve is closed



9

Design change

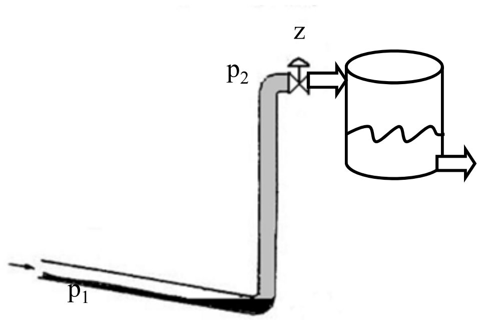
Avoid slugging:
2. Design change to avoid slugging



10

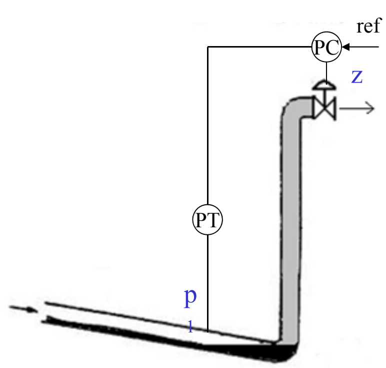
Design change

Minimize effect of slugging:
3. Build large slug-catcher



- Most common strategy in practice

Avoid slugging:
4. "Active" feedback control



Simple PI-controller

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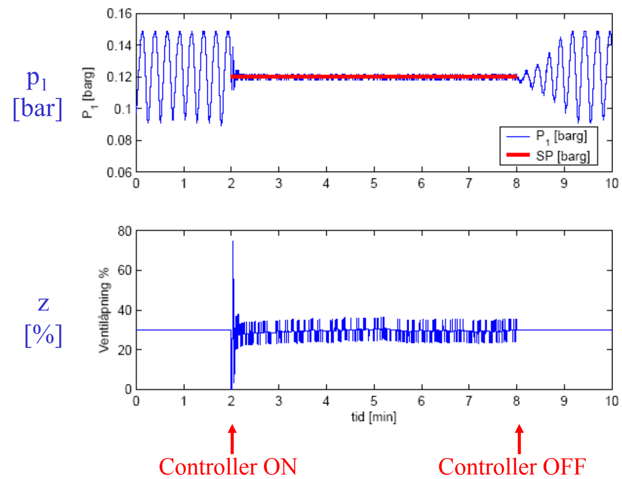
Anti slug control: Mini-loop experiments



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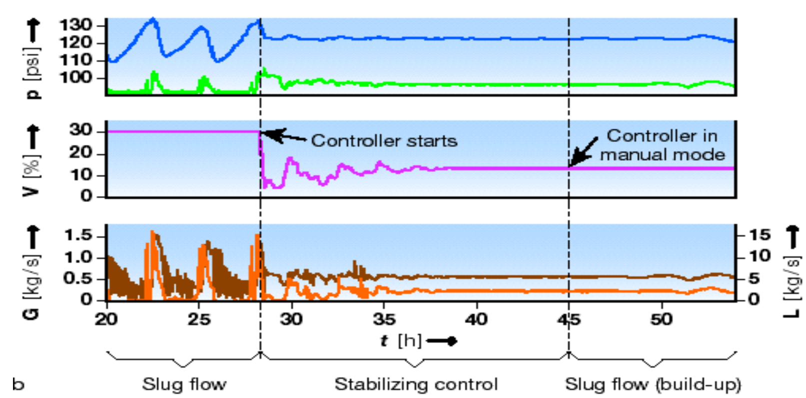
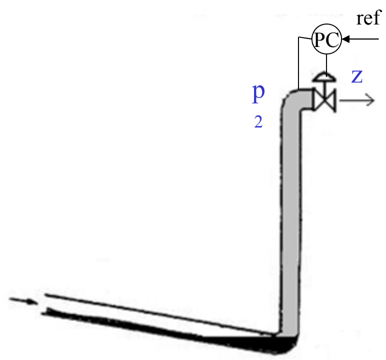
Anti slug control: Full-scale offshore experiments at Hod-Vallhall field (Havre,1999)



Avoid slugging:
5. ”Active” feedback control with topside measurement?



Control is difficult
(Inverse reponse = Unstable zero dynamics)

Summary anti slug control (2008)*

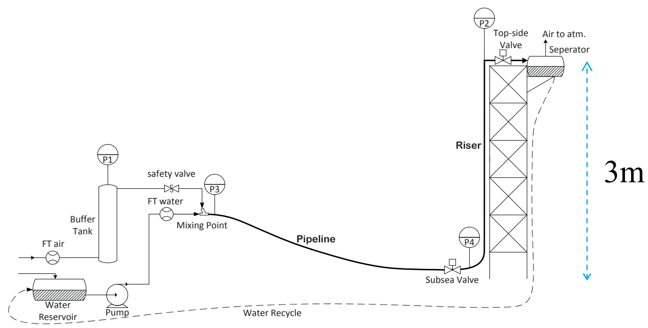
- Stabilization of desired non-slug flow regime = $$$$!
- Stabilization using downhole pressure simple
- Stabilization using topside measurements difficult
- Control can make a difference!

- “Only” problem: Not sufficiently robust

*Thanks to: Espen Storkaas + Heidi Sivertsen + Håkon Dahl-Olsen + Ingvald Bårdsen

2009-2013: Esmaeil Jahanshahi, PhD-work supported by Siemens

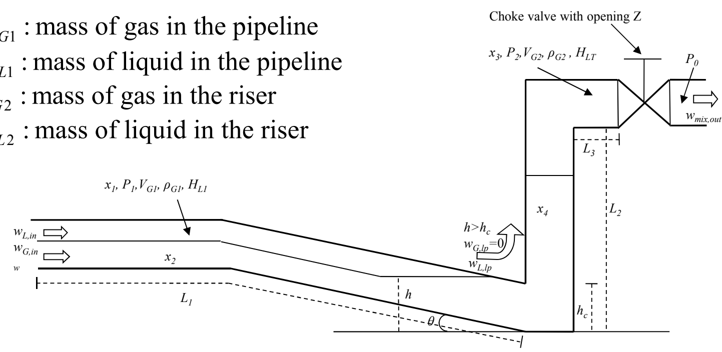
New Experimental mini-rig



17

1st step: Developed new simple 4-state model*

m_{G1} : mass of gas in the pipeline
m_{L1} : mass of liquid in the pipeline
m_{G2} : mass of gas in the riser
m_{L2} : mass of liquid in the riser



State equations (mass conservations law):

$$\dot{m}_{G1} = w_{G,in} - w_{G,lp}$$
$$\dot{m}_{L1} = w_{L,in} - w_{L,lp}$$
$$\dot{m}_{G2} = w_{G,lp} - w_{G,out}$$
$$\dot{m}_{L2} = w_{L,lp} - w_{L,out}$$

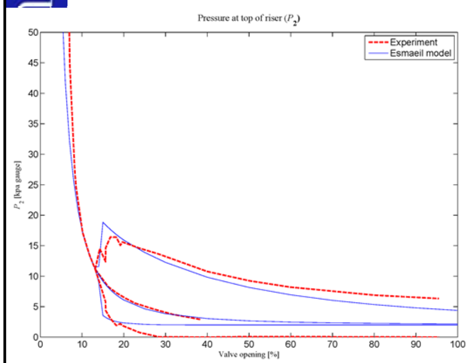
18

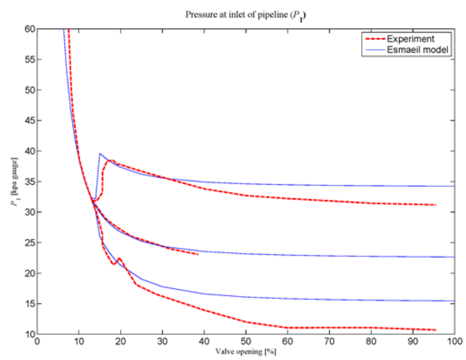
*Based on Storkaas model

New 4-state model. Comparison with experiments:

Top pressure

Subsea pressure



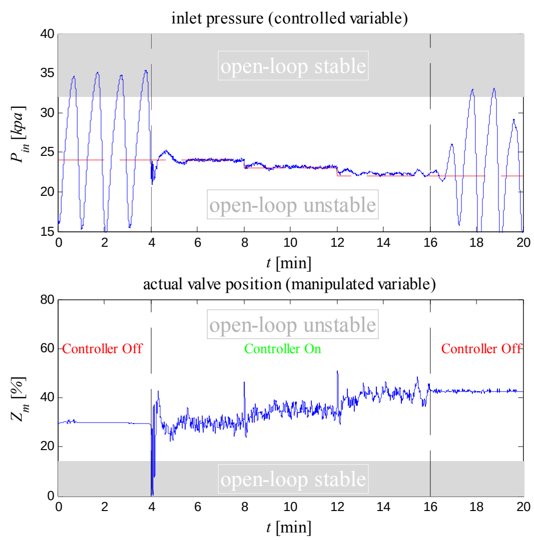


Linear Control Solutions

Experiment

Solution 1: H$_\infty$ control based on linearizing new model

Experiment, mixed-sensitivity design



$$\min_K \|N(K)\|_\infty, \quad N \triangleq \begin{bmatrix} W_u KS \\ W_T T \\ W_P S \end{bmatrix}$$

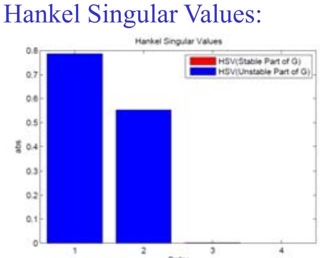
$$K = \frac{-257.77(s^2+0.0046s+0.002}{s(s+0.26)(s+4.9)}$$

Experimental linear model (new approach)

Fourth-order mechanistic model:

$$G(s) = \frac{\theta_1(s+\theta_2)(s+\theta_3)}{(s^2-\theta_4 s+\theta_5)(s^2+\theta_6 s+\theta_7)}$$

Hankel Singular Values:

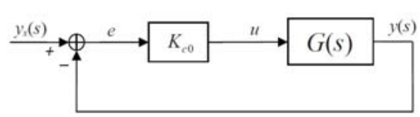


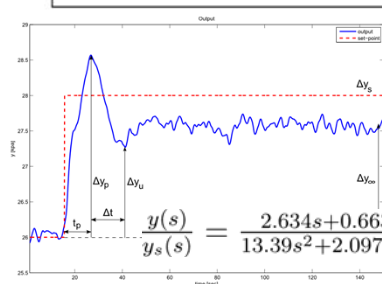
Model reduction:

$$G(s) = \frac{b_1 s+b_0}{s^2-a_1 s+a_0}$$

4 parameters need to be estimated

Closed-loop step-response with P-control





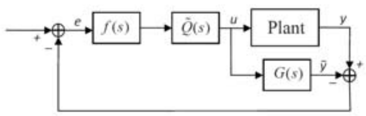
$$\frac{y(s)}{y_s(s)} = \frac{2.634s+0.6635}{13.39s^2+2.097s+1}$$

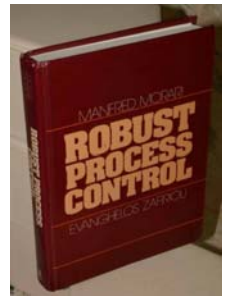
$$G(s) = \frac{-0.0098s-0.0025}{s^2-0.0401s+0.0251}$$

Solution 2: IMC based on identified model

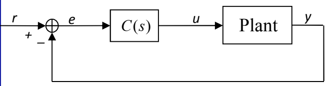
IMC design

Block diagram for Internal Model Control system





IMC for unstable systems:



$$C(s) = \frac{\tilde{Q}(s)f(s)}{1 - G(s)\tilde{Q}(s)f(s)}$$

Model:

$$G(s) = \frac{-0.0098s - 0.0025}{s^2 - 0.0401s + 0.0251}$$

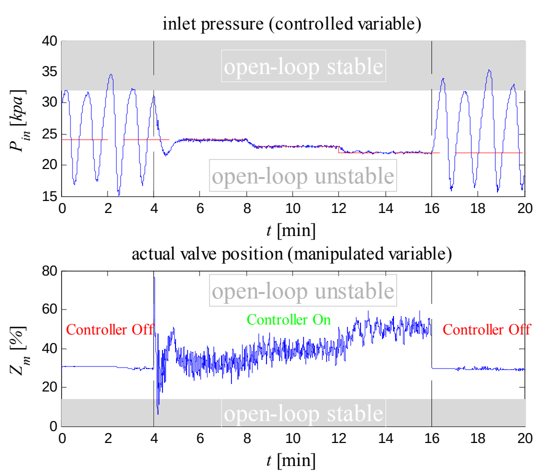
IMC controller: $\lambda = 8\ s$

$$C(s) = \frac{-42.20(s^2 + 0.052s + 0.0047)}{s(s + 0.251)}$$

Experiment

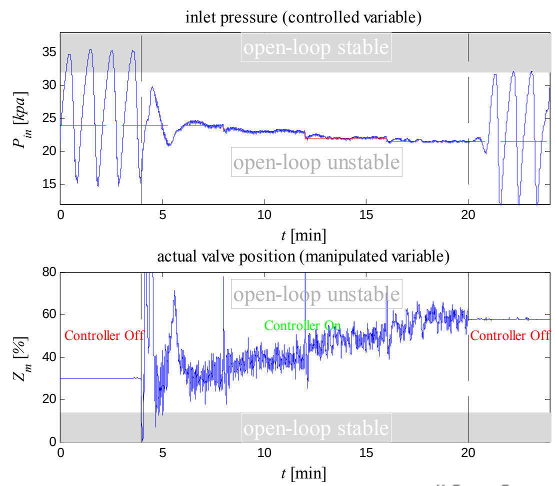
Solution 2: IMC based on identified model

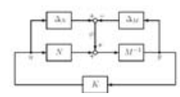
Experiment



Experiment

Solution 3: «Robustified» IMC using H_∞ loop shaping





$$\gamma_K = \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M^{-1} \right\|_\infty \le \frac{1}{\epsilon}$$

Comparing linear controllers (subsea pressure)

Comparison between IMC-PID controller and $\mathcal{H}_\infty$ controllers

	IMC-PID	$\mathcal{H}_\infty$ mixed-sensitivity	$\mathcal{H}_\infty$ loop-shaping
Gain Margin	0.38	0.46	0.29
GM Frequency	0.19	0.18	0.16
Phase Margin	61.68	50.63	64.44
PM Frequency	0.52	0.43	0.64
Delay Margin	2.07	2.07	1.77
$\|S\|_\infty$	1.02	1.17	1.14
$\|T\|_\infty$	1.63	1.86	1.41
$\|KS\|_\infty$	43.17	36.86	55.67
Z_{max}*	50%	50%	58%

*Controllers tuned at 30% valve opening

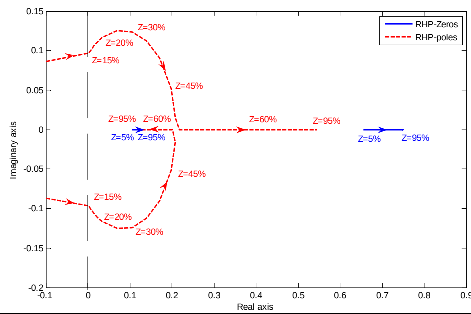
Fundamental limitation – top pressure

Measuring topside pressure we can stabilize the system only in a limited range

Unstable (RHP) zero dynamics of top pressure

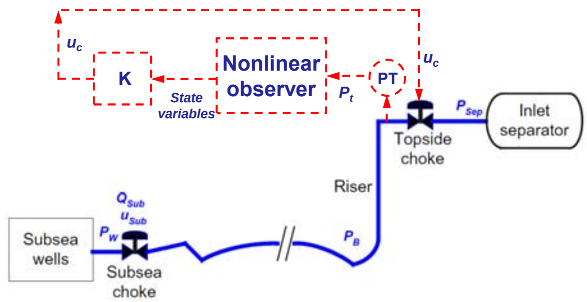
$$M_{S,\min} = \prod_{i=1}^{N_p} \frac{|z+p_i|}{|z-p_i|}$$

	Z = 20%	Z = 40%
$M_{s,min}$	2.1	7.0



Nonlinear Control Solutions

Solution 1: observer & state feedback



High-Gain Observer

$$\dot{\hat{z}}_1 = f_1(\hat{z})$$

$$\dot{\hat{z}}_2 = f_2(\hat{z})$$

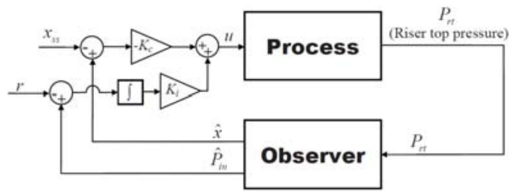
$$\dot{\hat{z}}_3 = f_3(\hat{z}) + \frac{1}{\varepsilon}(y_m - \hat{y})$$

$$\dot{\hat{z}}_4 = f_4(\hat{z})$$

z_1 : mass of gas in the pipeline (m_{gp})
z_2 : mass of liquid in the pipeline (m_{lp})
z_3 : pressure at top of the riser ($P_{r,t}$)
z_4 : mass of liquid in the riser (m_{lr})

$$P_{r,t} = \frac{m_{gr} R T_r}{M_G (V_r - \frac{m_{Lr}}{\rho_l})}$$

State Feedback

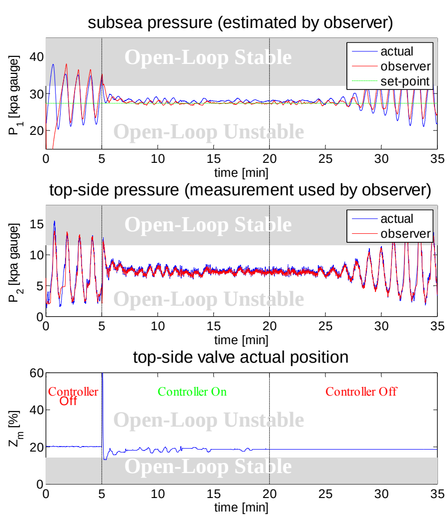


$$u(t) = -K_c(\hat{x}(t) - x_{ss}) + K_i \int_0^t (\hat{P}_{in}(\tau) - r)\, d\tau$$

K_c : linear optimal gain calculated by solving *Riccati equation*
K_i : small integral gain (e.g. $K_i = 10^{-3}$)

Experiment

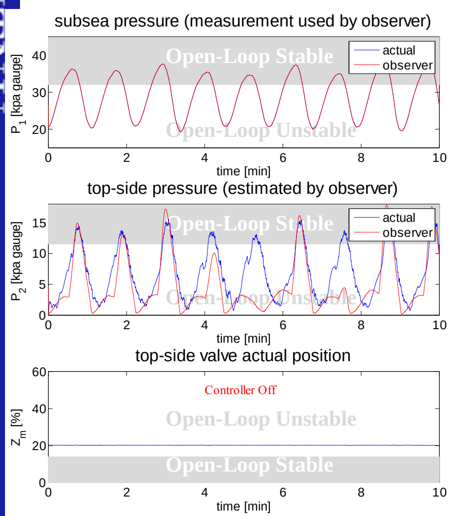
High-gain observer – top pressure



measurement: topside pressure
valve opening: 20 %

Experiment

High-gain observer – subsea pressure

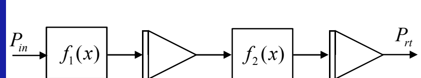


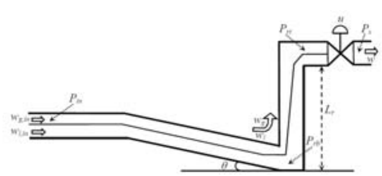
measurement: subsea pressure
valve opening: 20 %

Not working ??!

Chain of Integrators

- Fast nonlinear observer using subsea pressure: Not Working??!
- Fast nonlinear observer (High-gain) acts like a differentiator
- Pipeline-riser system is a chain of integrator
- Measuring top pressure and estimating subsea pressure is differentiating
- Measuring subsea pressure and estimating top pressure is integrating





Nonlinear observer and state feedback

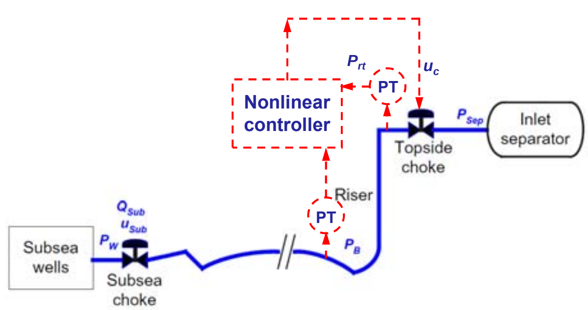
Summary

- Anti-slug control with top-pressure is possible using fast nonlinear observers
- The operating range of top pressure is still less than subsea pressure
- Surprisingly, nonlinear observer is not working with subsea pressure, but a (simpler) linear observer works very fine.

	Subsea pressure	Top Pressure
Nonlinear Observer	Not Working !?	Working*
Linear Observer	Working	Not Working
PI Control	Working	Not Working
Max. Valve	60%	20%

*but only for small valve openings

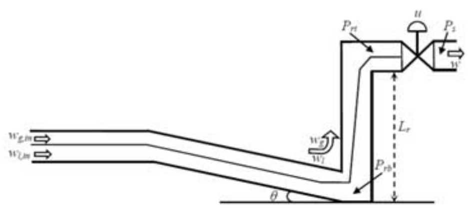
Solution 2: feedback linearization

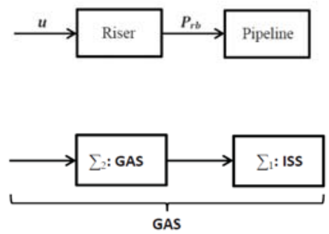


Jahanshahi, Skogestad and Grøtli, NOLCOS, 2013

Solution 2: feedback linearization

Cascade system





Output-linearizing controller

Stabilizing controller for riser subsystem

System in normal form:

ξ: riser-base pressure η: top pressure

$$\dot{\xi} = (w_g + w_l)\,[F(\xi,\eta) + c] - [F(\xi,\eta) + c]\,w$$
$$\dot{\eta} = (w_g + w_l)F(\xi,\eta) - F(\xi,\eta)w,$$

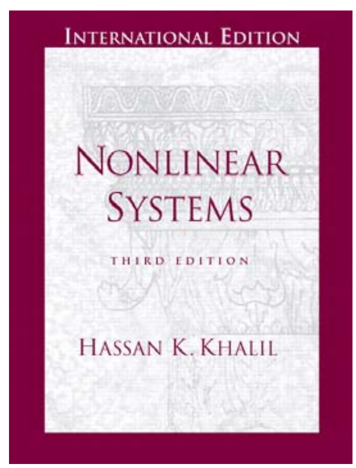
Linearizing controller:

$$w = \frac{w_{in}(F(y)+c) + K_1(y_1 - \bar{y}_1)}{F(y)+c}$$
$$\dot{\xi} = -K_1\xi$$

η dynamics bounded

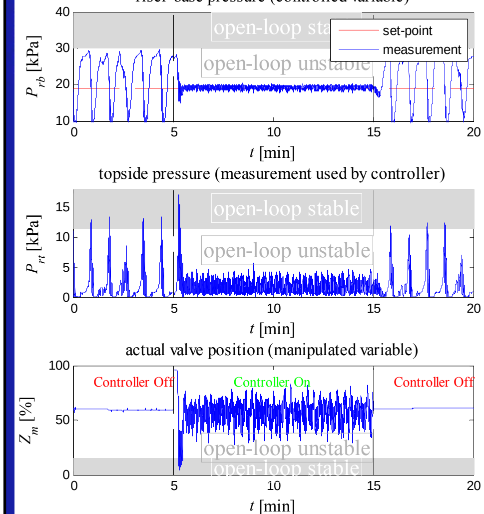
Control signal to valve:

$$u = \text{sat}\left(\frac{w}{C_v\sqrt{\rho_{rt}(y_2 - P_s)}}\right)$$



Experiment

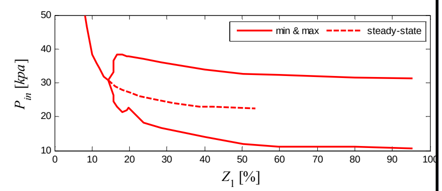
CV: riser-base pressure (y_1), Z=60%



$$w = \frac{w_{in}(F(y)+c)+K_1(y_1-\bar{y}_1)}{F(y)+c}$$

$$u = \text{sat}\left(\frac{w}{C_v\sqrt{\rho_{rt}(y_2-P_s)}}\right)$$

$$\text{Gain: } \frac{\partial y}{\partial u} = \frac{\partial P_{in}}{\partial Z}$$

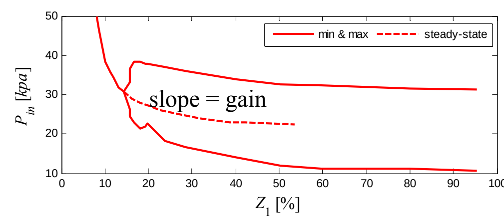


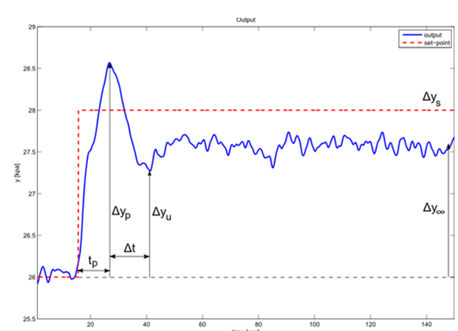
Solution 3: Adaptive PI Tuning

Static gain: $\frac{\partial y}{\partial u} = \frac{\partial P_{in}}{\partial Z}$

$$k(z) = \frac{-2\bar{a}\frac{\partial f(z)}{z}}{f(z)^3}$$

Linear valve: $k(z) = \frac{-2\bar{a}}{z^3}$





PI Tuning:

$$\beta = \frac{-\ln\left(\frac{\Delta y_\infty - \Delta y_u}{\Delta y_p - \Delta y_\infty}\right)}{2\Delta t} + \frac{K_{c0}k(z_0)\left(\frac{\Delta y_p - \Delta y_\infty}{\Delta y_\infty}\right)^2}{4t_p}$$

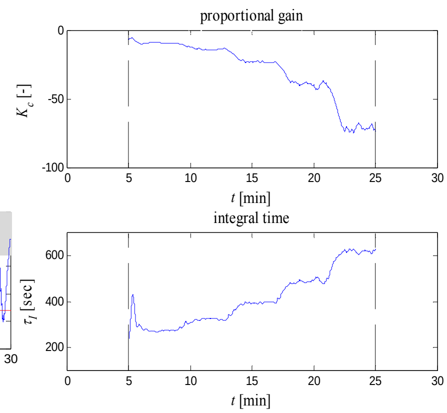
$$K_c(z) = \frac{\beta T_{osc}}{k(z)\sqrt{z/z^*}}$$

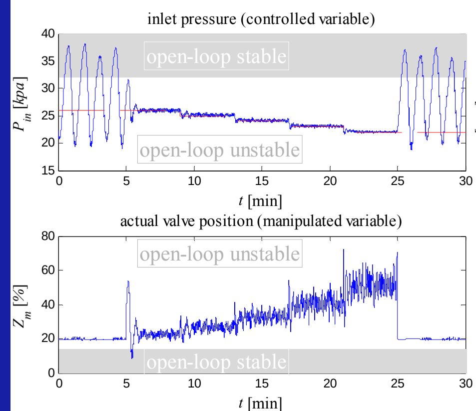
$$\tau_I(z) = 3T_{osc}(z/z^*)$$

Experiment

Solution 3: Adaptive PI Tuning

Experiment





Solution 4: Gain-Scheduling IMC

Three identified model from step tests:

Z=20%: $G_1(s) = \dfrac{-0.015(s+0.26)}{s^2 - 0.045s + 0.0094}$

Z=30%: $G_2(s) = \dfrac{-0.0098(s+0.25)}{s^2 - 0.040s + 0.025}$

Z=40%: $G_3(s) = \dfrac{-0.0056(s+0.27)}{s^2 - 0.017s + 0.096}$

Three IMC controllers:

$$C_1(s) = \frac{-16.15(s^2 + 0.016s + 0.0012)}{s(s+0.26)}$$

$$C_2(s) = \frac{-42.20(s^2 + 0.052s + 0.0047)}{s(s+0.25)}$$

$$C_3(s) = \frac{-115.11(s^2 + 0.052s + 0.014)}{s(s+0.27)}$$

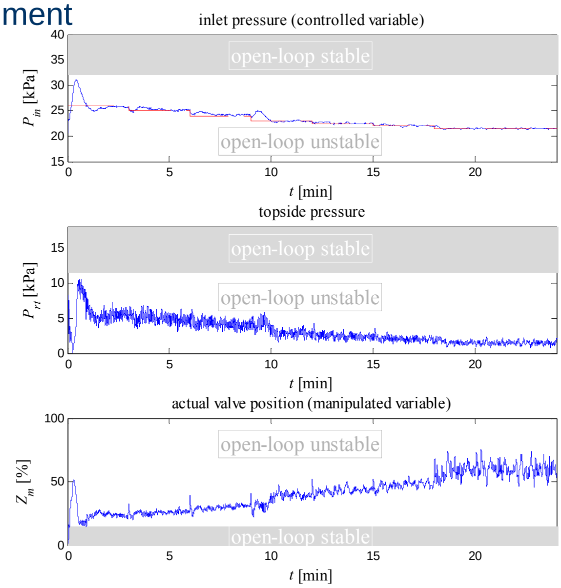
Gain-scheduling logic

Pressure set-point	Controller
$P_{set} \geq 24\ kPa$	$C_1(s)$
$24\ kPa > P_{set} > 21.5\ kPa$	$C_2(s)$
$P_{set} \leq 21.5\ kPa$	$C_3(s)$

Experiment

Solution 4: Gain-Scheduling IMC

Experiment



Comparison of Nonlinear Controllers

- Gain-scheduling IMC is the most robust solution
- Adaptive PI controller is the second-best
- Controllability remarks:
  - Fundamental limitation control: gain of the system goes to zero for fully open valve
  - Additional limitation top-side pressure: Inverse response (non-minimum-phase)

	CV	$\theta = 0$	$\theta = 1$	$\theta = 2$
Gain-scheduling IMC	P_{in}	60%	60%	50%
Adaptive PI	P_{in}	60%	50%	32%
Output linearization	P_{rb} & P_{rt}	60%	40%	25%
Nonlinear observer	P_{rt}	28%	24%	22%

Conclusions

- A new simplified model verified by OLGA simulations and experiments
- Best: Anti-slug control using a subsea valve close to riser-base
- New robust controllers have been developed
- Main point: Increase controller gain for large valve openings

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