System Identification Procedures for Resonance Frequency Control of SC Cavities

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ACCELENCE

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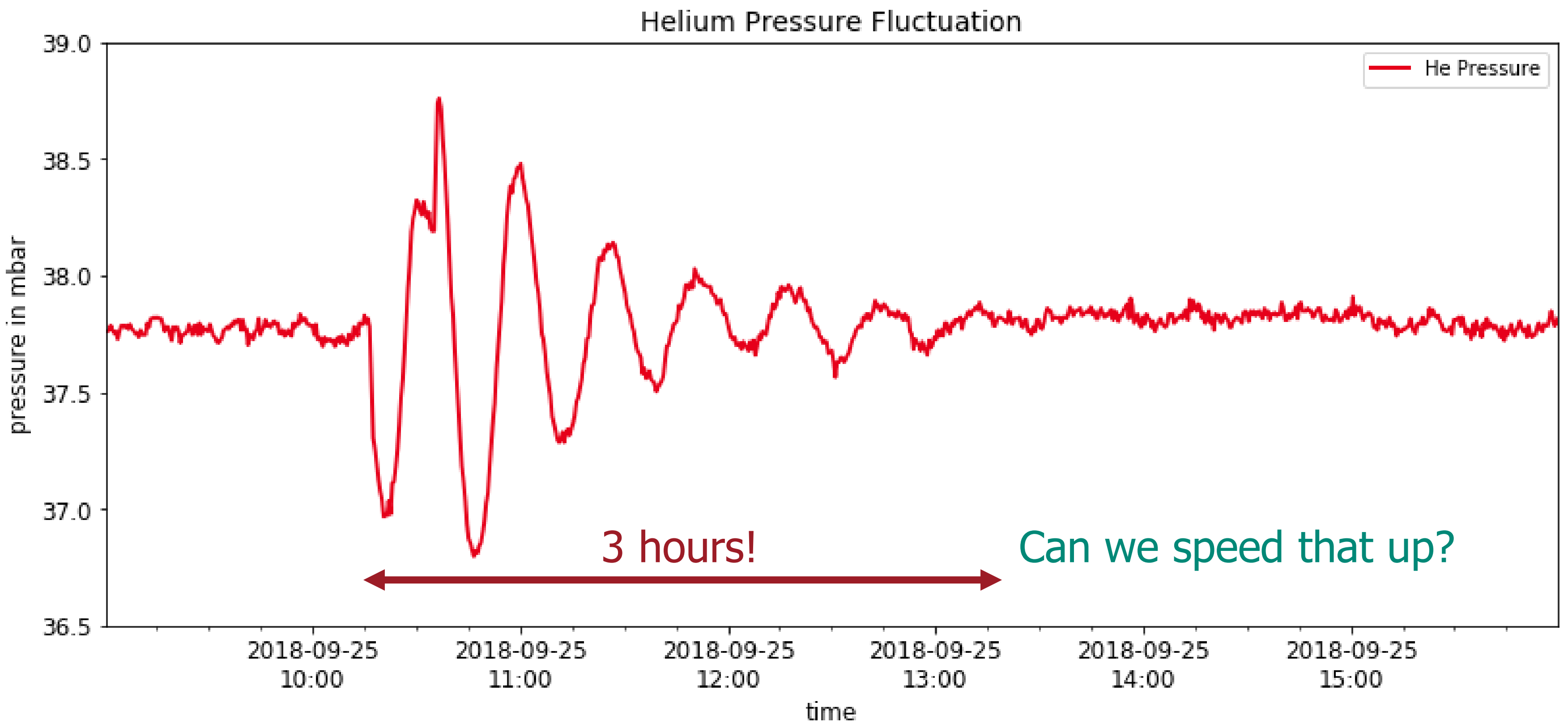
TEMF

Motivation:
Helium Pressure Fluctuations



Outline

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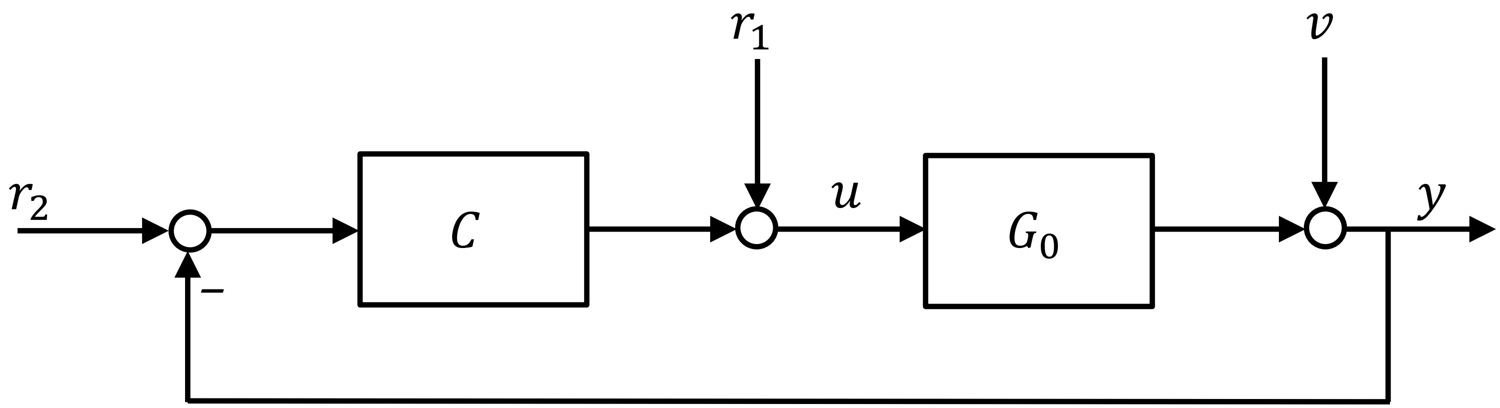
- Motivation
- Setup to be considered
- Closed-Loop System Identification
- Optimization of the Control Parameters
- Measurements with the new Control Parameters
- Summary & Outlook

Setup to be considered



$r(k) = r_1(k) + C(z) r_2(k)$

$v(k) = H_0(z) e(k)$ (filtered white noise)

$S_0 = (1 + G_0 C)^{-1}$ (sensitivity function)

$y(k) = S_0 G_0 r(k) + S_0 H_0 e(k)$

$u(k) = S_0 r(k) - S_0 C H_0 e(k)$

- note: nonparametric (spectral) estimate of G_0:
  - open loop: $\hat{G}(e^{j\omega}) = \frac{\hat{\Phi}_y}{\hat{\Phi}_u}$ (using the spectra)
  - closed loop: $\hat{G}(e^{j\omega}) = \frac{\hat{\Phi}_{yr}}{\hat{\Phi}_{ur}}$ (using the cross-spectra)

Closed-Loop System Identification:
Direct Identification – *Open-Loop Like*

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- controller output $u_i \longrightarrow$ plant output y_i (C can be unknown)
- transfer function $G(z) = \frac{b_{n-1}z^{-1}+\cdots+b_0z^{-n}}{1+a_{n-1}z^{-1}+\cdots+a_0z^{-n}} = \frac{B(z^{-1})}{A(z^{-1})}$ (order n known)
- parameters a_i, b_i combined into θ
- equation error $\tilde{\epsilon}_k(\theta) = y_k - G(z,\theta)u_k$
- least-squares problem: minimize $J = \tilde{\epsilon}_k^{\mathrm{T}}\tilde{\epsilon}_k$
- bias-free and consistent in the ARX-case, i.e. $H(z) = \frac{1}{A(z^{-1})}$ and if u_i and v_i are uncorrelated (not the case in closed-loop operation, but can be mitigated with good SNR at u_i, i.e. large excitation r_i)

Closed-Loop System Identification:
Direct Identification – *Prediction Error Method*

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- controller output $u_i \longrightarrow$ plant output y_i (C can be unknown)
- transfer function $G(z) = \frac{b_{n-1}z^{-1}+\cdots+b_0 z^{-n}}{1+a_{n-1}z^{-1}+\cdots+a_0 z^{-n}} = \frac{B(z^{-1})}{A(z^{-1})}$ ($H(z)$ analog)
- parameters a_i, b_i, ... combined into θ
- *prediction* error $\epsilon_k(\theta) = H^{-1}(z,\theta)(y_k - G(z,\theta)u_k)$
- least-squares problem: minimize $V = \epsilon_k^{\mathrm{T}}\epsilon_k$
- bias-free and consistent if the *whole true system* $S \coloneqq (G_0, H_0)$ is present in the model set $\mathcal{M} \coloneqq \{(G(z,\theta), H(z,\theta)), \theta \in \Theta\}$
  ➔ accurately specified noise model needed! (good SNR at u_i also reduces the bias)
- not suitable for reduced-order (approximate) model identification

Closed-Loop System Identification: Indirect Identification

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General Idea

- identify $G_{\text{cl}} = \frac{G_0}{1+G_0 \cdot C} \quad (r \longrightarrow y)$ from $y(k) = G_{\text{cl}} r(k) + H_{\text{cl}} e(k)$ with open-loop techniques (r and e are uncorrelated!)
- solve $\hat{G}_{\text{cl}}$ for $\hat{G}_0$ (e.g. using knowledge of C) ➔ typically results in high-order estimates!
- may use specialized parametrizations
  - *coprime factorization* (lower order)
  - *dual Youla-Kučera* (stabilization of $\hat{G}_0$ with C guaranteed)

Two-Stage Method

- rewrite the system equations:

  $y(k) = G_0 u_r(k) + S_0 v(k)$

  $u(k) = u_r(k) - S_0 C v(k)$

  $u_r(k) \coloneqq S_0 r(k)$

1. identify $S_0 = \frac{1}{(1+G_0 C)} \; (r_1 \longrightarrow u)$ from $u(k) = S(z,\beta) r_1(k) + We(k)$ with PEM and simulate "noise-free" input $\hat{u}_r(k) = S\left(z,\hat{\beta}\right) r_1(k)$
2. apply a LS criterion to the PE $\epsilon_k(\theta) = K^{-1}(z,\theta)(y_k - G(z,\theta)\hat{u}_r)$ ➔$\hat{G}_0 = G\left(z,\hat{\theta}\right)$, $\hat{H}_0 = K\left(z,\hat{\theta}\right) S^{-1}\left(z,\hat{\beta}\right)$

- free choice of order of $G(z,\theta)$!
- knowledge of C not required

Closed-Loop System Identification:
Indirect Identification – "*PT2 & PID" assumption*

- identified system is the closed-loop system $G_{\mathrm{cl}} = \frac{G_{\mathrm{He}} \cdot C}{1 + G_{\mathrm{He}} \cdot C}$ $\quad (r_2 \longrightarrow y)$

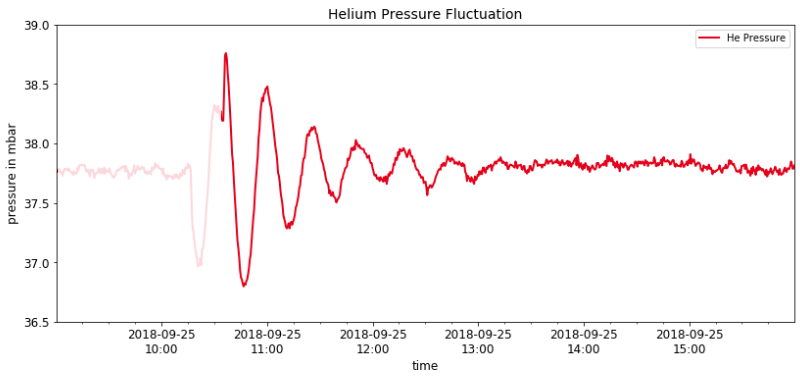
  with the controller $C(s) = \mathrm{P} + \frac{1}{\mathrm{I}s} + \mathrm{D}s$

- extract the He-pressure system TF G_{He}:

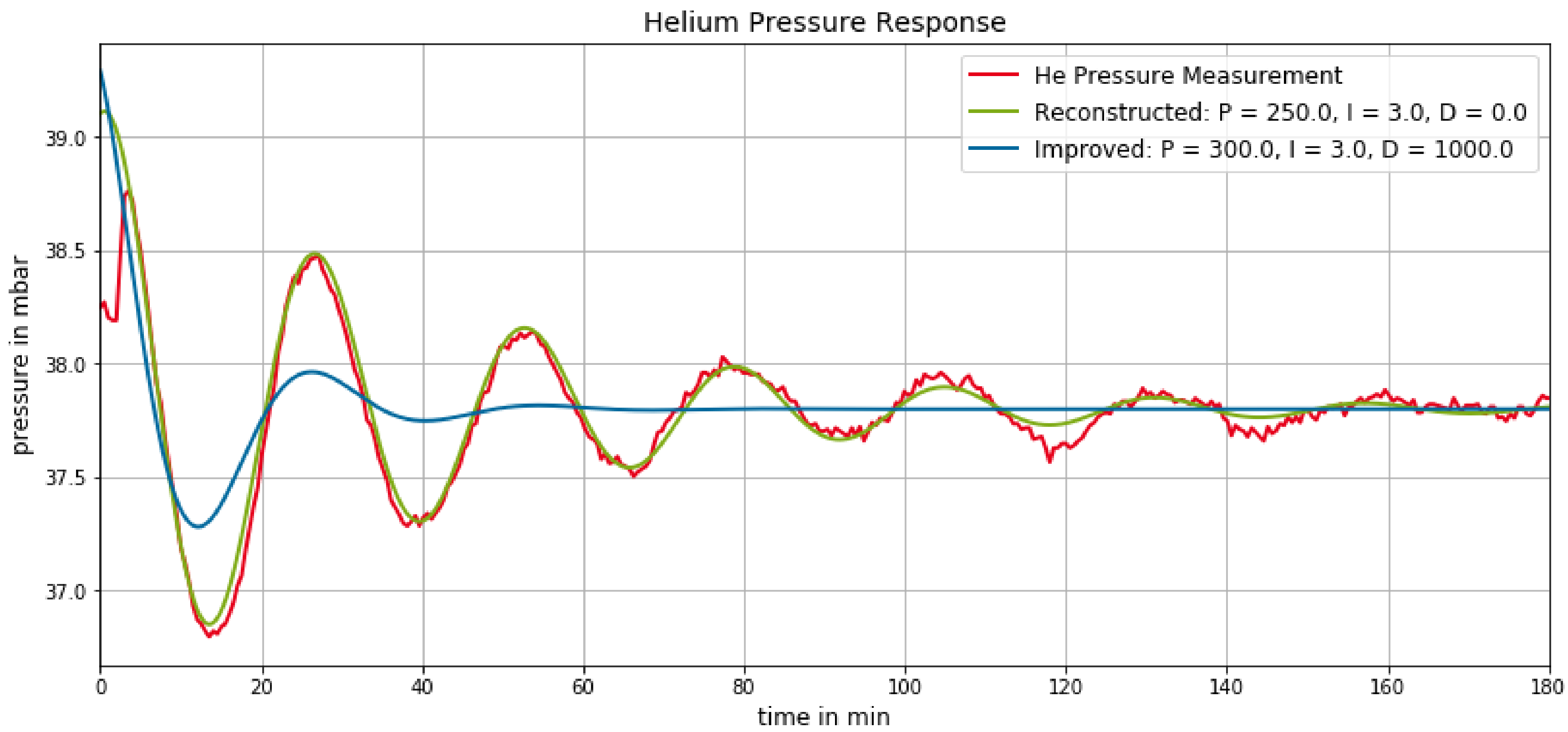
$$G_{\mathrm{He}} = \frac{G_{\mathrm{cl}}}{C(1 - G_{\mathrm{cl}})} = \frac{3.988 \cdot 10^{-5} s}{s^2 - 9.034 \cdot 10^{-3} s + 2.901 \cdot 10^{-6}}$$

additional zero to reproduce jumps (already introduced in G_{cl})

PT2 behaviour



Optimization of the Control Parameters



Measurements with the new Control Parameters

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- testing of new parameters ($\mathrm{P} = 300,\ \ \mathrm{I} = 3\ s,\ \mathrm{D} = 1000\ s$)
  - measurements taken on 17. December 2018, between 07:30 am and 11:00 am
  - new parameters applied at 10:31 am

- some difficulties:
  - Christmas shut-down preparation in progress
  - He-level quite low, three of four pumps run at idle and He-pressure is nevertheless well below its set-point
  - need to turn one more pump off

Measurements with the new Control Parameters

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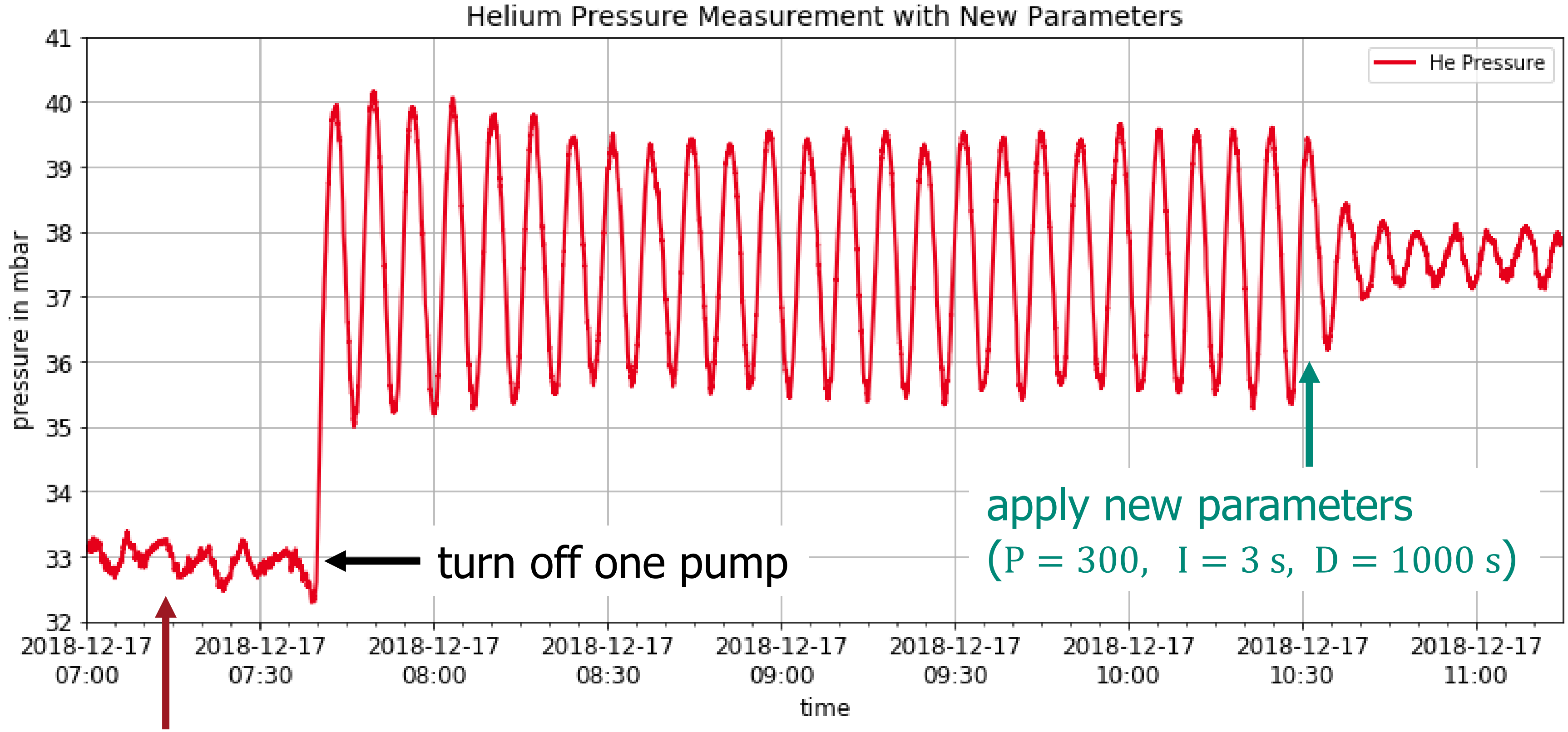

He-level very low, three pumps run at idle (old parameters: $P = 250, \quad I = 3\,\text{s}, \quad D = 0\,\text{s}$)

Summary & Outlook

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- different system identification procedures for model-based controller tuning during closed-loop operation were presented
  - direct method $(u \longrightarrow y)$ ➔ prediction error (least squares)
  - indirect method $(r \longrightarrow y)$ ➔ two-stage (via $G_{\mathrm{cl}} = S_0 G_0$)
- first test with improved control parameters gave promising results

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- comparison of different estimation techniques for validation and benchmarking are yet to be done
- further investigations with different excitation signals r are planned
- methods shall be applied to more LLRF components

THANK YOU
FOR YOUR ATTENTION!