Presentation of Master's Thesis

Investigation of Control Approaches for a High Precision, Piezo-actuated Rotational Stage

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Introduction

CERN

The Large Hadron Collider (LHC) at CERN.

Source: [1].

Collimation

Collimation system used in the LHC.

Source: [1].

Crystal Collimation

The UA9 collaboration at CERN investigates how bent crystals can be used to extract halo particles.

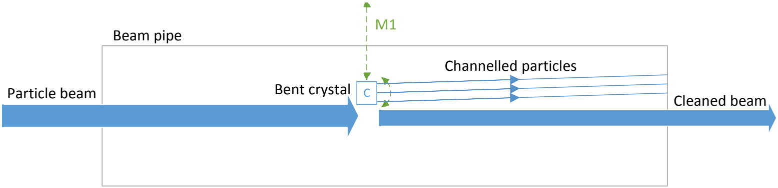


Figure 1: Illustration of the crystal collimation principle.

Implies in a more efficient cleaning, a less complex system and a reduction of the machine impedance.

Purpose and Goal

The **higher the energy** of the particle the **lower the angular acceptance** for channeling.

- have a total range of $20\,\mathrm{mrad}$
- be able to track reference trajectories at ramp rates of $100\,\mu\mathrm{rad/s}$
- reject external disturbances to maintain a maximum tracking error of $\pm 1\,\mu\mathrm{rad}$ even when the linear axis is moving

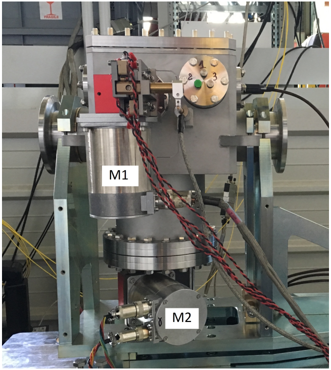
Challenges

- Nonlinear effect such as hysteresis and creep
- Highly resonant structure
- The linear movement adds additional perturbation
- System changes due to rotational and linear position, moving center of rotation.

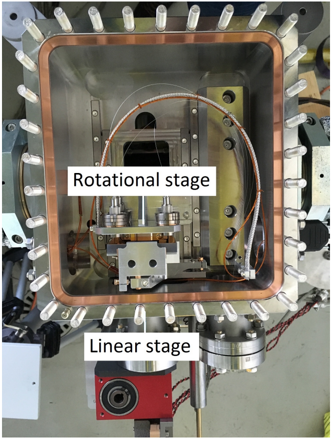
Method

- Literature study
- Further investigation of selected control approaches
- Benchmarking tests of selected control approaches in simulations
- Implementation of the most promising approach
- Proposal of controller

System Overview



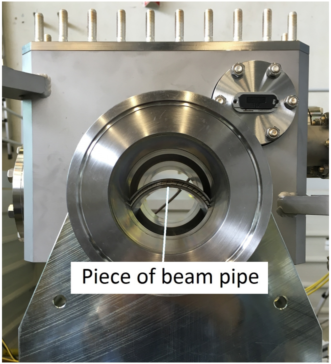
Side view



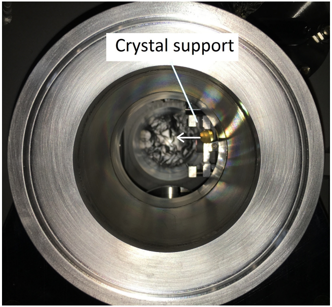
Top view

Figure 2: The new collimator from the side (a) and the top (b).

Crystal Collimator



Giving access

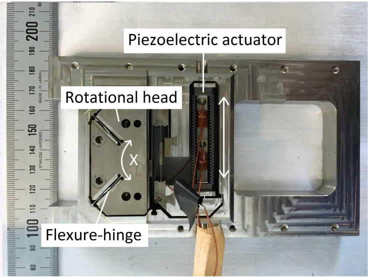


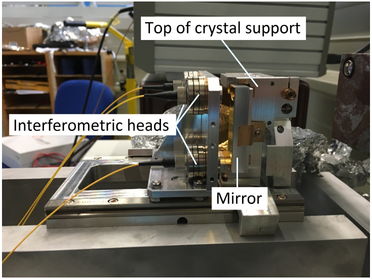
Insertion of crystal

Figure 3: The new collimator with the beam pipe piece half-way out (a) and the crystal inserted into the beam pipe (b).

Rotational Stage

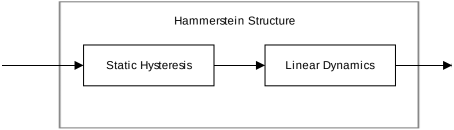
- Monolithic structure to avoid sliding parts
- Piezoelectric stack actuator
- Displacement: 0 to $30\ \mu\mathrm{m} \implies$ 0 to 20 mrad
- Nonlinear effects

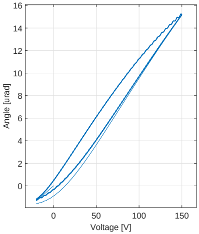


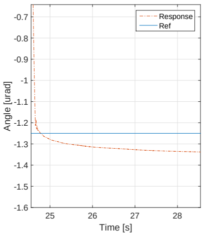


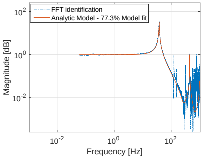
Modeling

- Hysteresis effect - Modeled by a Maxwell slip model
- Creep effect - Efficiently eliminated in closed loop
- Rotational stage - modeled as a Hammerstein structure









Linear System Identification

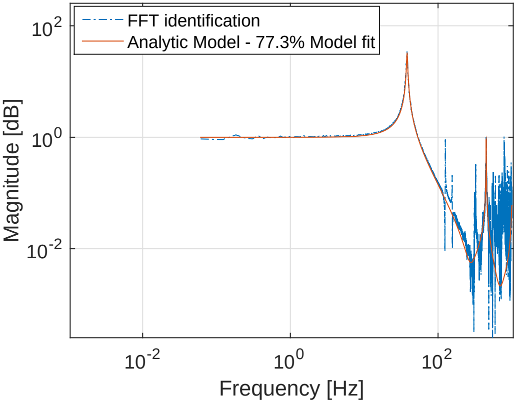
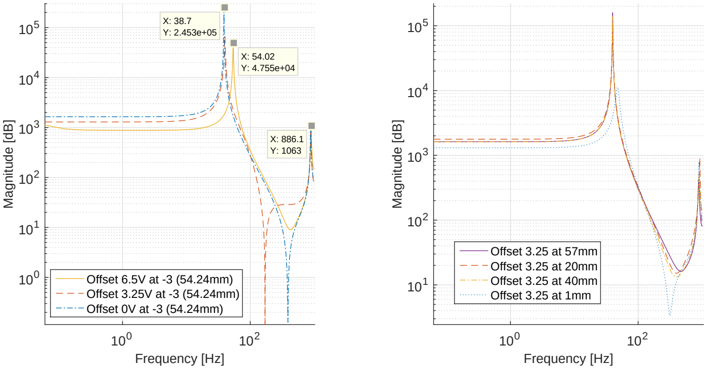


Figure 4: Model fit of the system model with 5 zeros and 6 poles to the FFT of the acquired data.



Different rotational head positions

Different linear axis positions

Figure 5: Identified models with different rotational positions (linear axis in 54.24 mm) is shown in (a) and with different linear axis positions (rotational position corresponding to 3.25 V) is shown in (b).

Present Control Approach

2-DOF structure, feedback and prefilter. C is a series combination of a:

- PID - for stablity
- Notch filter - to cancel high frequency oscillations
- Lead filter - to increase the phase margin

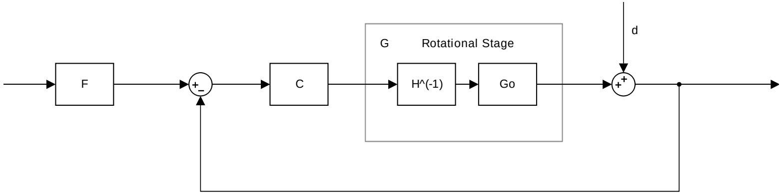


Figure 6: Block diagram of the present control loop, including controller, prefilter and hysteresis compensator.

Approaches and Simulation Results

Model Reference Adaptive Controller

Idea: Adapt to model changes and compensate for nonlinear effects.

- Uses a reference model to create the desired system response.
- Based on Lyapunov theory
- Sufficient with a low order model
- Nonlinear effects is seen as lumped perturbations.

Model Reference Adaptive Controller

System model

$$\ddot{x}(t) + \alpha_1 \dot{x}(t) + \alpha_0 x(t) = \beta_0 u(t) + f(t)$$

Reference model

$$\ddot{x}_m(t) + a_1 \dot{x}_m(t) + a_0 x_m(t) = b_0 u_d(t)$$

Final control law

$$u(t) = k_0 u_d(t) + (k_1 + k_3 \alpha_0) x(t) + (k_2 + k_3 \alpha_1) \dot{x}(t) + k_3 \ddot{x}(t) - k_3 \beta_0 u(t - T_s)$$

where the control law parameters are calculated as outlined below.

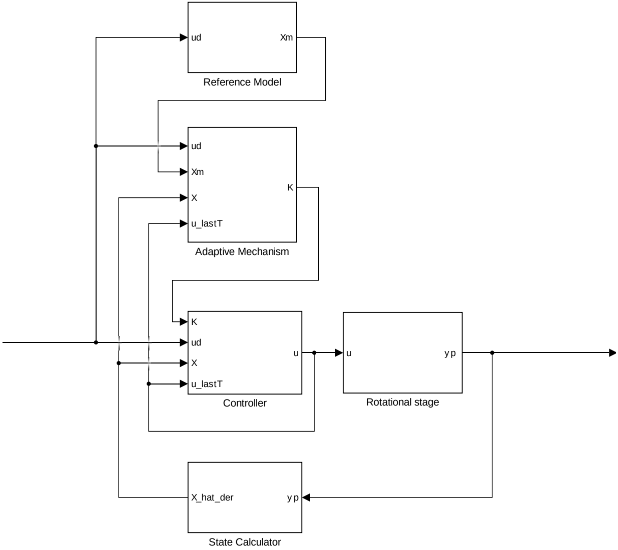
$$\dot{k}_0 = -\eta_0 \hat{e} u_d$$

$$\dot{k}_1 = -\eta_1 \hat{e} x$$

$$\dot{k}_2 = -\eta_2 \hat{e} \dot{x}$$

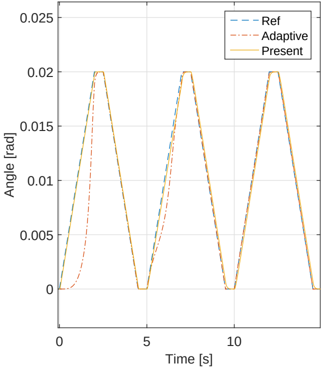
$$\dot{k}_3 = -\eta_3 \hat{e} \hat{f}$$

Model Reference Adaptive Controller

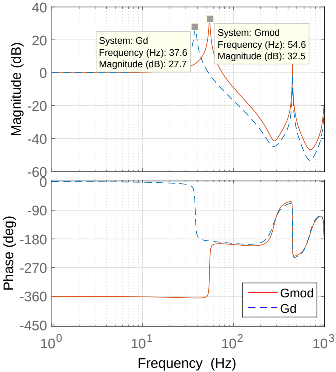


Model Reference Adaptive Controller

Periodic response with model parameter drift increased linearly from $t = 5$ s to $t = 7$ s.



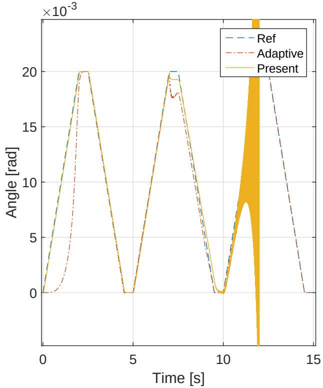
Periodic response



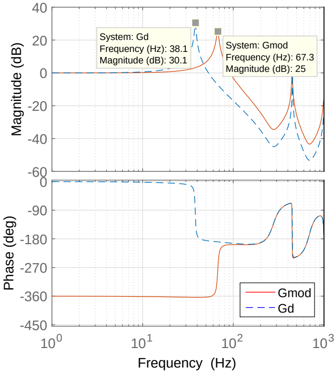
Model change

Model Reference Adaptive Controller

Periodic response with model parameter drift increased linearly from $t = 7$ s to $t = 9$ s.



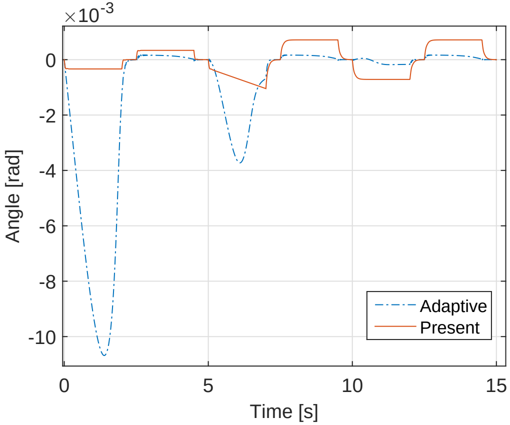
Periodic response



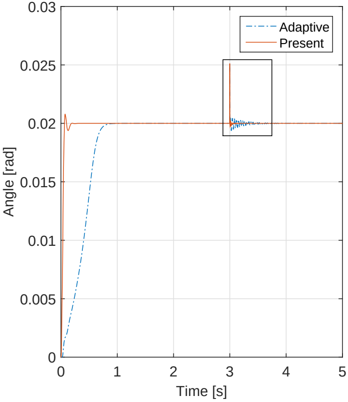
Model change

Model Reference Adaptive Controller

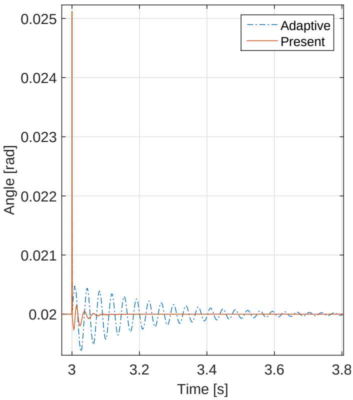
Tracking error



Model Reference Adaptive Controller



Step response



Zoom-in on disturbance

Integral Resonance Control

Idea: Increase the tracking accuracy and reduce the sensitiveness to model errors.

- Uses a constant feed-through term to damp out the first resonance peak
- Simple integral controller is used for inner-loop stability
- Increases the closed loop bandwidth implying in a better tracking performance.
- Interesting for long and short term effects.

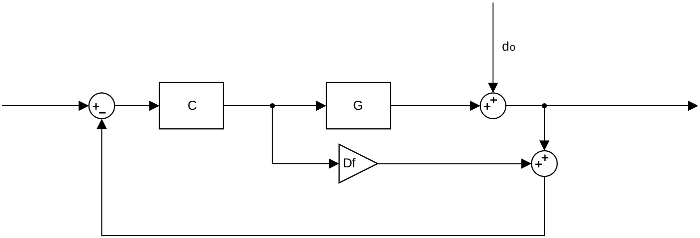


Figure 8: Block diagram of the IRC damping loop.

$$C_2(s) = \left.\frac{C(s)}{1 + C(s)D_f}\right|_{C(s)=\frac{-k}{s}} = \frac{-k}{s - kD_f} \qquad (1)$$

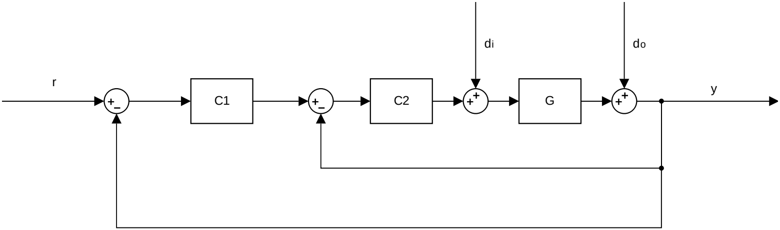


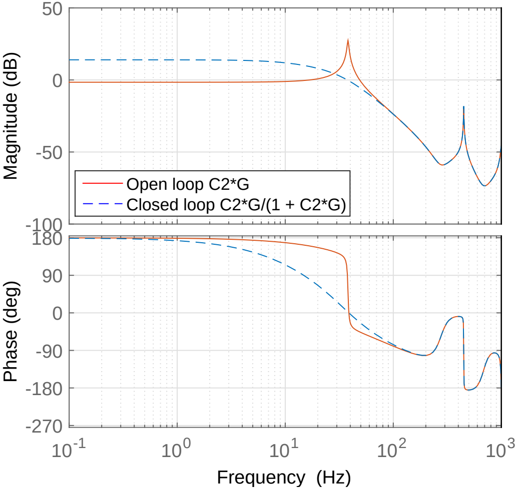
Figure 9: Block diagram of the tracking control system with IRC included.

$$G_c(s) = \frac{C_1(s)C_2(s)G(s)}{1 + C_2(s)G(s) + C_1(s)C_2(s)G(s)} \tag{2a}$$

$$S(s) = \frac{1}{1 + C_2(s)G(s) + C_1(s)C_2(s)G(s)} \tag{2b}$$

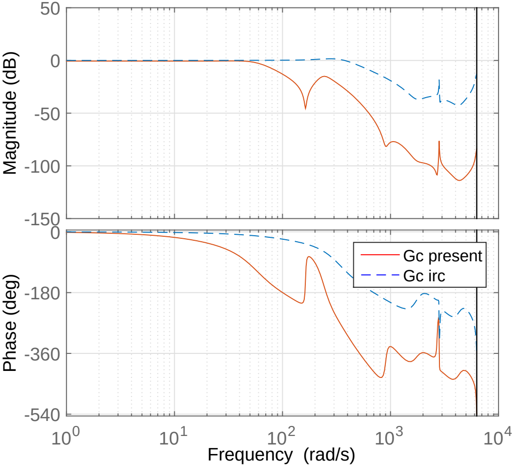
Integral Resonance Control

IRC-damping. Bode diagram of inner loop.



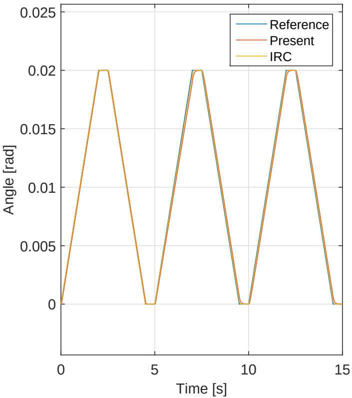
Integral Resonance Control

Increased the closed loop bandwidth from 11 Hz to 73 Hz.

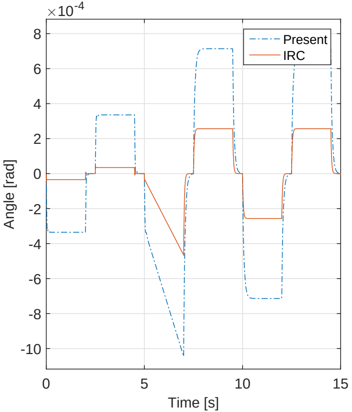


Integral Resonance Control

Periodic response with model parameter drift increased linearly from $t = 5$ s to $t = 7$ s.

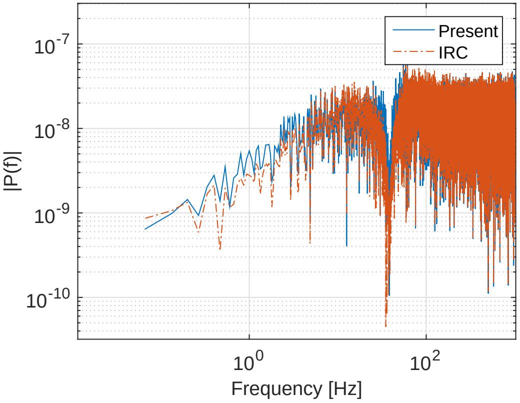


Periodic response



Tracking error

Integral Resonance Control



Harmonic Cancellation

Idea: Cancel out specific disturbances coming from the environment in the tunnel or the linear stage movement.

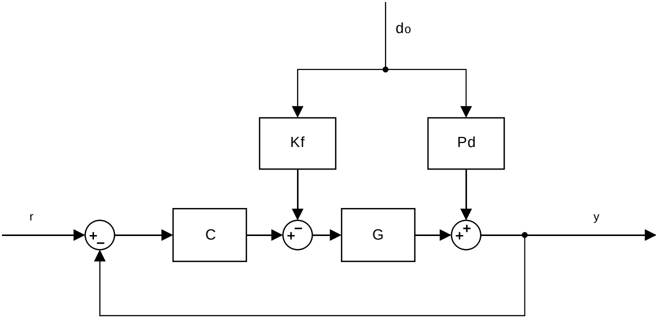
- Feedforward Disturbance Cancellation
- Cancellation with Internal Model Principle
- Repetitive Feedforward Disturbance Cancellation

Feedforward Disturbance Cancellation

Idea: Use a feedforward approach to cancel out known disturbances coming from the linear axis movement.

- Identify a static disturbance model
- Use the stepping signal as input to the model
- Disturbance must be measurable

Feedforward Disturbance Cancellation

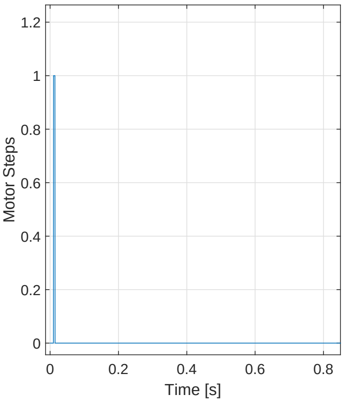


$$Y(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} R(s) + \frac{P_d(s) - K_f(s)G(s)}{1 + C(s)G(s)} D_0(s) \qquad (3)$$

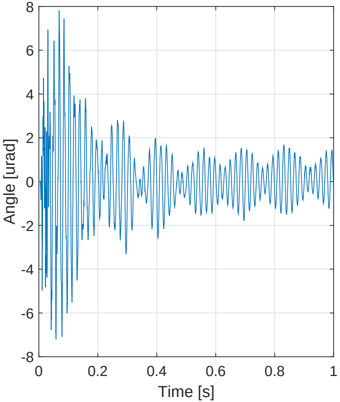
Ideal choice: $K_f(s) = P_d(s)/G(s)$

$K_f(s)$ not implementable (stable, proper and causal). $\implies$ Approximate G.

Feedforward Disturbance Cancellation

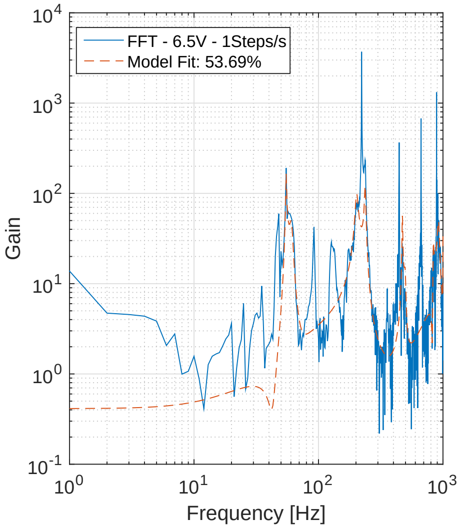


Impulse used as input signal

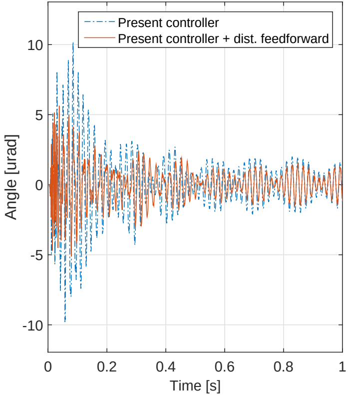


Mean of impulse responses

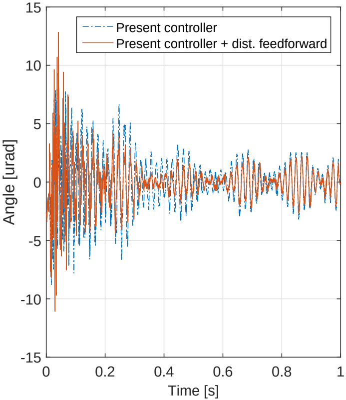
Feedforward Disturbance Cancellation



Feedforward Disturbance Cancellation



Mean as disturbance



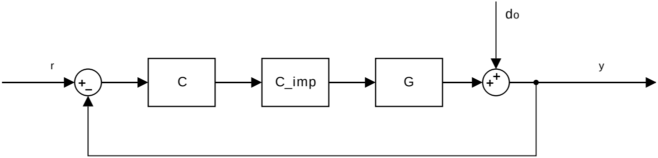
Original acquired signal as disturbance

Cancellation with Internal Model Principle

Idea: Include a inverse model of the disturbance in the feedback loop to cancel the harmonic.

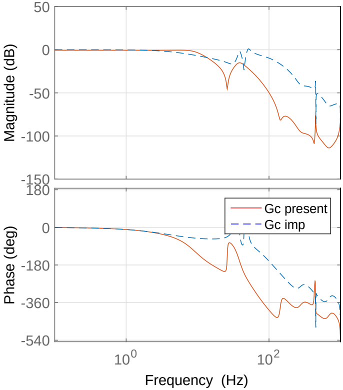
- Asymptotically reject the modeled disturbance
- Affecting the closed loop system

Cancellation with Internal Model Principle

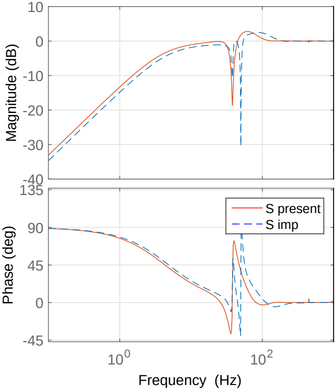


The generating polynomial $\Gamma(s) = f(0, s)/D(s)$.
$C_t(s) = P(s)/(\Gamma(s)\bar{L}(s))$.

Cancellation with Internal Model Principle

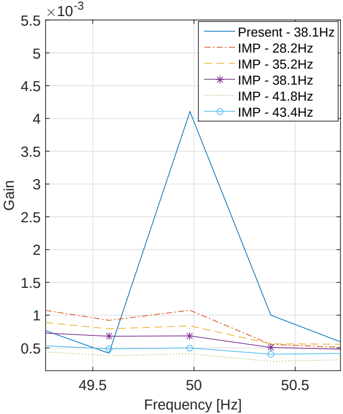


Closed loop system

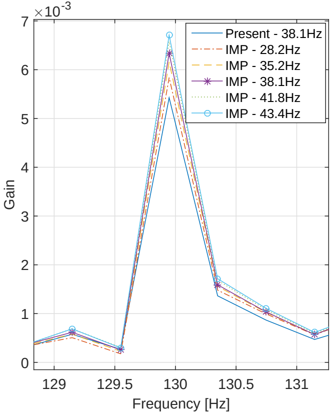


Sensitivity function

Cancellation with Internal Model Principle



Attenuation of selected frequency



Impact on 130 Hz component

Repetitive Feedforward Disturbance Cancellation

Idea: Use an observer to estimate and cancel known disturbances without affecting the closed loop system.

- First introduced for the control of hard disks
- Feedforward switching mechanism with an observer
- Disturbance is observed, saved and replicated
- Reject multiple disturbances

The state space system and observer is given as

$$\dot{\mathbf{x}}(t) = \mathbf{A_c}\mathbf{x}(t) + \mathbf{B_c}\big(u(t) + d_o(t)\big) \tag{4a}$$

$$y(t) = \mathbf{C_c}\mathbf{x}(t) \tag{4b}$$

$$\dot{\mathbf{x}}_d(t) = \mathbf{A_d}\mathbf{x_d}(t) \tag{4c}$$

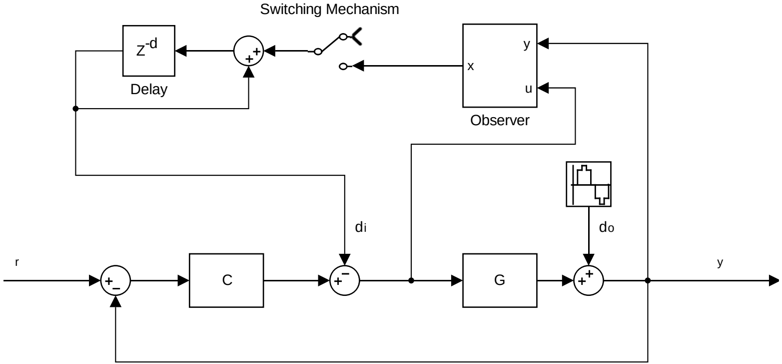
$$d_o(t) = \mathbf{C_d}\mathbf{x_d}(t) \tag{4d}$$

$$\mathbf{A_d} = \begin{bmatrix} 0 & 1 \\ -w^2 & 0 \end{bmatrix} \qquad \mathbf{C_d} = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{5}$$

$$\hat{\mathbf{x}}[n+1] = \mathbf{A}\hat{\mathbf{x}}[n] + \mathbf{B}u[n] + \mathbf{K}(\mathbf{y}[n] - \mathbf{C}\hat{\mathbf{x}}[n]) \tag{6}$$

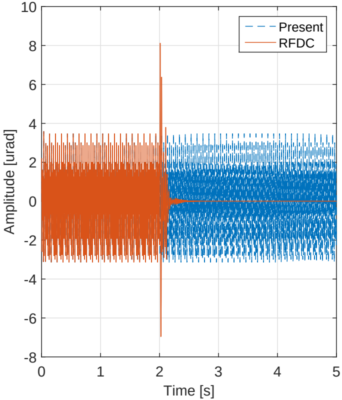
$$\mathbf{A} = \begin{bmatrix} \mathbf{A_{zs}} & \mathbf{C_{zd}}\mathbf{B_{zs}} \\ \mathbf{0} & \mathbf{A_{zd}} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} \mathbf{B_{zs}} \\ \mathbf{0} \end{bmatrix} \qquad \mathbf{C} = \begin{bmatrix} \mathbf{C_{zs}} & \mathbf{0} \end{bmatrix} \tag{7}$$

Repetitive Feedforward Disturbance Cancellation

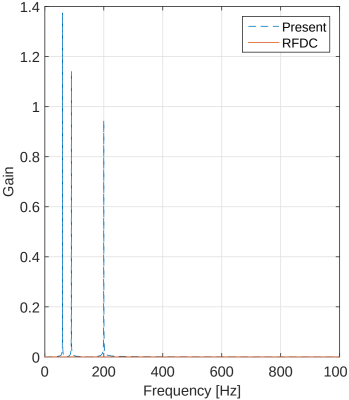


Repetitive Feedforward Disturbance Cancellation

Cancellation of the 60, 90 and the 200 Hz



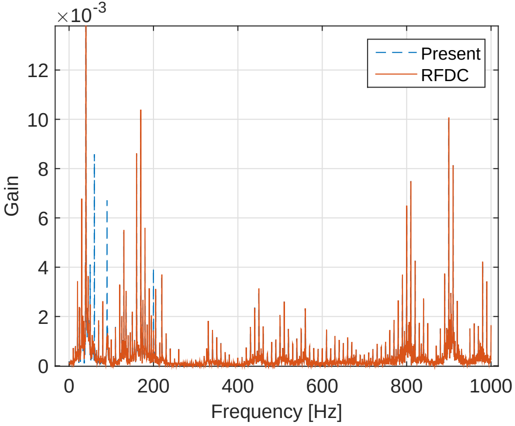
Time domain



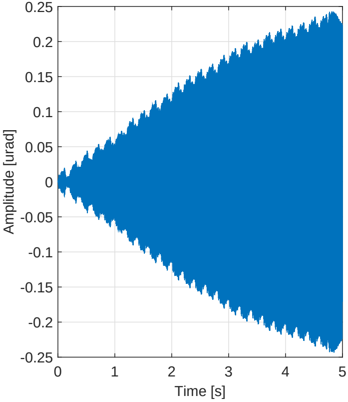
FFT

Repetitive Feedforward Disturbance Cancellation

Multiple harmonic cancellation with real acquired disturbances



Repetitive Feedforward Disturbance Cancellation



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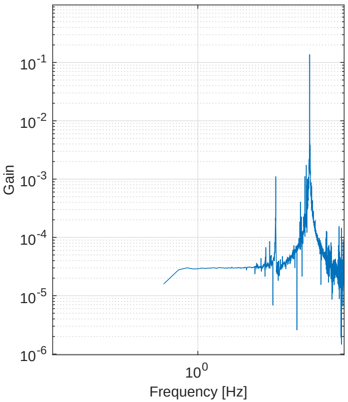
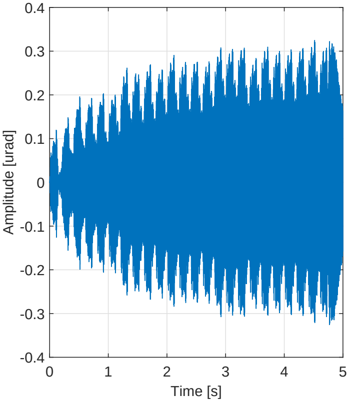


FFT

Repetitive Feedforward Disturbance Cancellation



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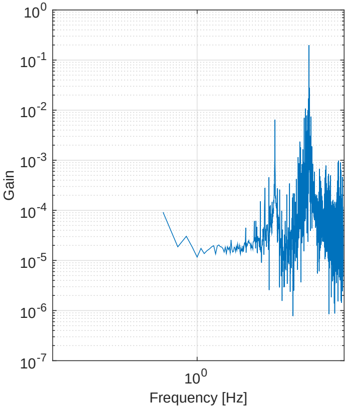


FFT

Comparison

No	Aspect	Present	IRC	MRACPE
1	Closed-loop Bandwidth [Hz]	9.7	73.3	-
2	Gain/Phase margin [dB / °]	14.4/66.2	13.1/49.4	-
3	Tracking error, periodic input σ-[mrads]	0.29	0.03	0.11
4	Tracking error with model errors (model's 1st resonance at 22.0Hz), σ-[mrads]	∞	0.03	0.21
5	Tracking error with model errors (model's 1st resonance at 67.2Hz), σ-[mrads]	∞	0.03	0.11
6	Tracking error with model errors (model's 1st resonance at 17.6Hz), σ-[mrads]	∞	∞	0.47
7	Tracking error with model errors (model's 1st resonance at 77.7Hz), σ-[mrads]	∞	∞	0.11

Comparison

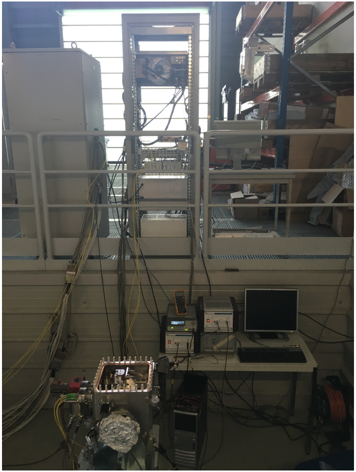
No	Aspect	Present	IRC	MRACPE
8	Output disturbance rejection, settling time (1%) [ms]	8	25	260
9	Input/Output disturbance rejection, σ-[$\mu\mathrm{rad}$]	0.68/1.43	0.45/1.46	1.95/1.41
10	Stability issues	Unstable with high model errors	Unstable with high model errors, but better than present	Good adaption even with model errors, but tuning for quicker adaption easily leads to instability. Stability only proven in continuous time.
11	Design and implementation considerations	Straight-forward technique, allowing for basic stability analysis	Same as present	Hard to tune. High computational burden for higher order models.

Comparison

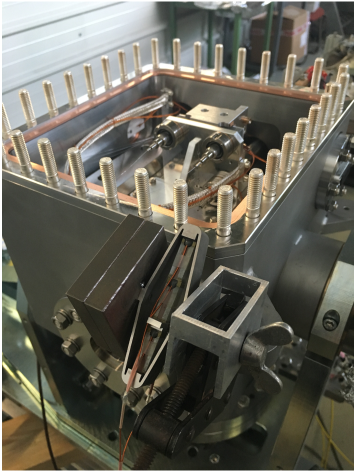
No	Aspect	FDC	RFDC	IMP
1	Affecting closed loop system	No	No	Yes
2	Cancellation effectiveness of major frequency, attenuation-[%]	64.6	88.4	83.3
3	Cancellation with model errors (model's 1st resonance at 28.2Hz), attenuation-[%]	40.5	26.6	73.5
4	Cancellation with model errors (model's 1st resonance at 43.4Hz), attenuation-[%]	57.7	5.0	83.4
5	Implementation considerations	Requires high order model, computational demanding.	Requires observer, computational demanding. Can be used as add-on.	Controller must be retuned when selecting a new frequency.

Implementation

Setup



Setup



Shaker

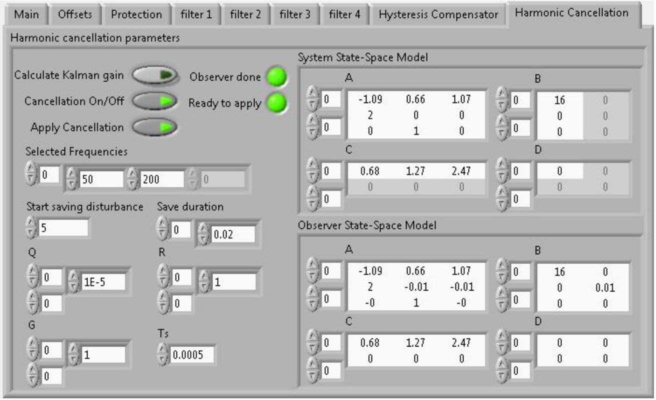
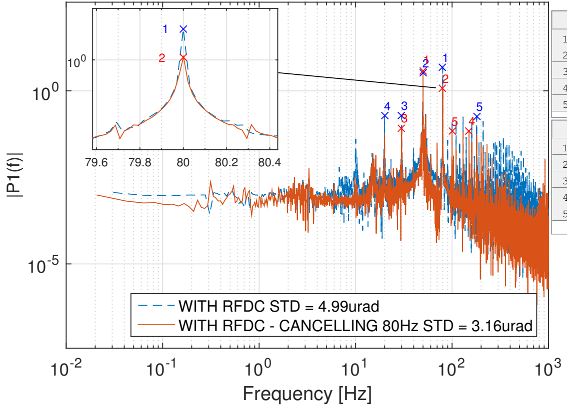


Figure 10: Graphical user interface of the RFDC implementation.

Single Disturbance

RFDC cancellation verification with disturbance added by shaker. 80 Hz component is reduced by 76% of its original amplitude.

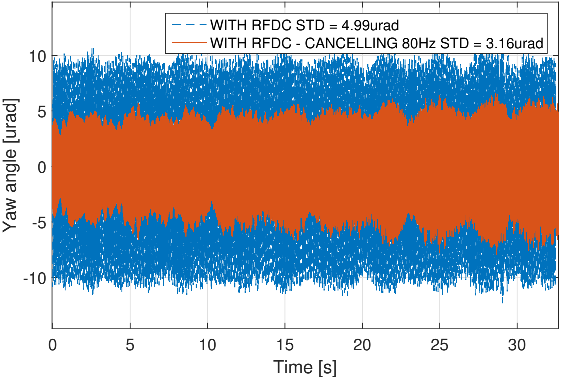


	Freq	Ampl
1	80	4.8068
2	50	3.3231
3	30	0.1980
4	19.9692	0.1911
5	179.9692	0.1847

	Freq	Ampl
1	49.9796	3.7916
2	80.0008	1.1617
3	30.0212	0.0846
4	149.9179	0.0691
5	99.9592	0.0678

Single Disturbance

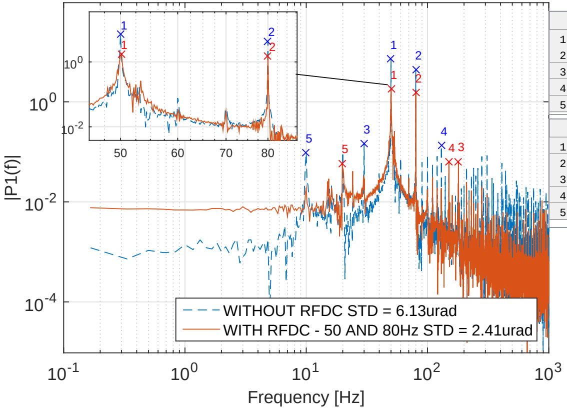
… which reduces the standard deviation significantly.



Multiple Disturbances

The cancellation of 50Hz and 80 Hz component under the first 10 s.

- 50Hz component reduced by 75%
- 80Hz component reduced by 66%

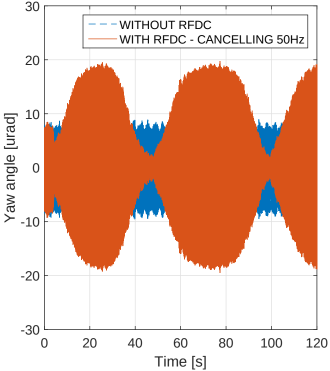


	Freq	Ampl
1	49.9958	7.1486
2	79.9933	4.4025
3	29.9975	0.1472
4	129.9892	0.1320
5	9.9992	0.0959

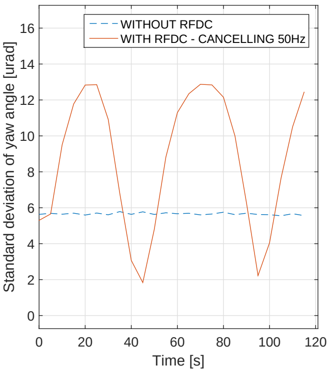
	Freq	Ampl
1	50.1625	1.7865
2	79.9933	1.5185
3	179.8183	0.0644
4	149.9875	0.0626
5	19.8317	0.0590

Beat effect

Cancellation performance in closed loop over 2 minutes.



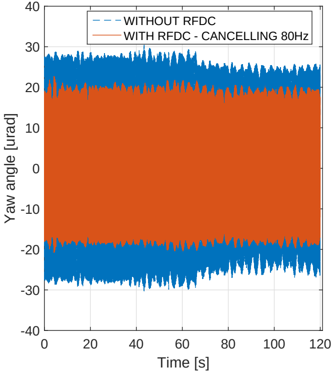
Yaw angle displacement



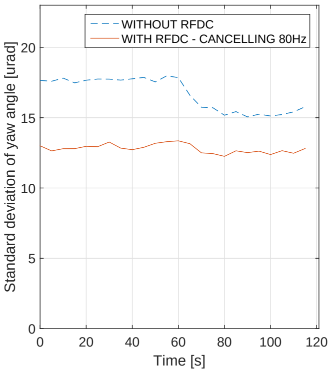
Standard deviation

Beat effect

Cancellation of artificial disturbances



Yaw angle displacement



Standard deviation

Conclusion

Simulation

IRC

- Can be used to efficiently increase the closed loop bandwidth
- 80Hz component reduced by 66%

MRACPE

- Can be used to adapt to large model changes and thereby prevent instability (way too significant)
- Stability depending on the step size
- Better for long term parameter adaption

RFDC

- Can be used to efficiently damp out known harmonic oscillations
- 80Hz component reduced by 66%

Implementation

Summary

Questions?

References I

H. G. Morales.
opac hector garcia morales - lhc collimation system optimization, 2015.
Available at https://www.youtube.com/watch?v=h2-ocLjUhTU.