

# Presentation of Master's Thesis

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

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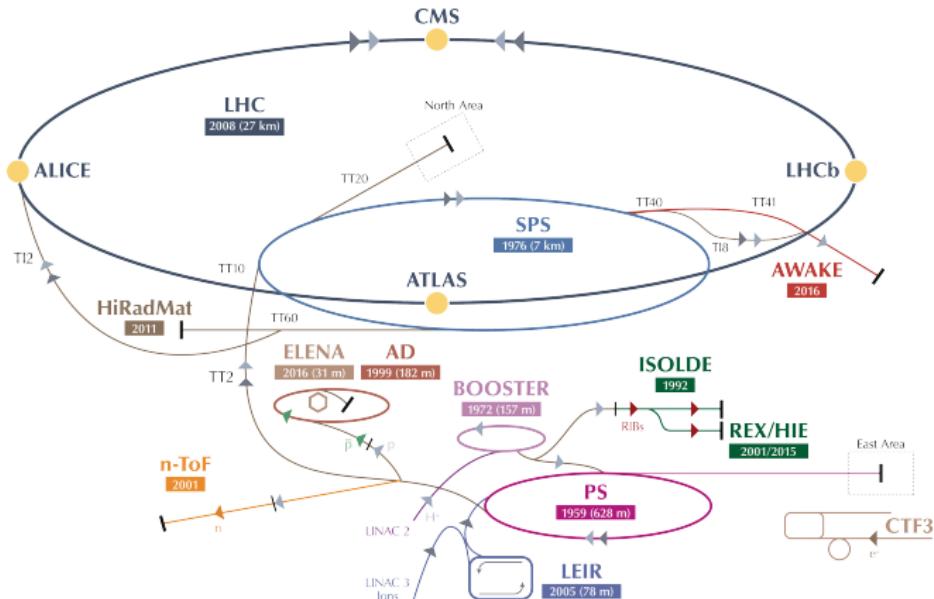


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# Introduction

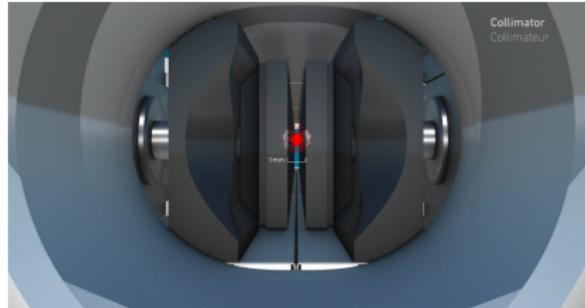
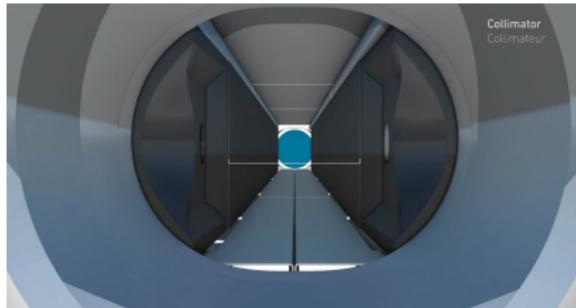
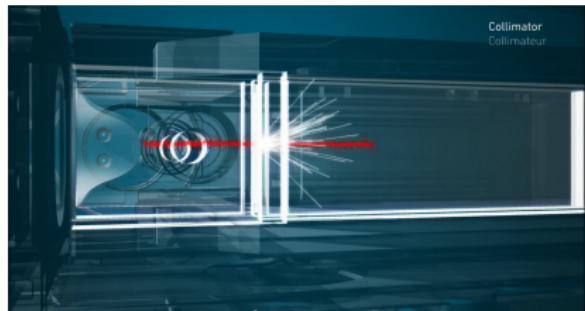
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Source: [1].

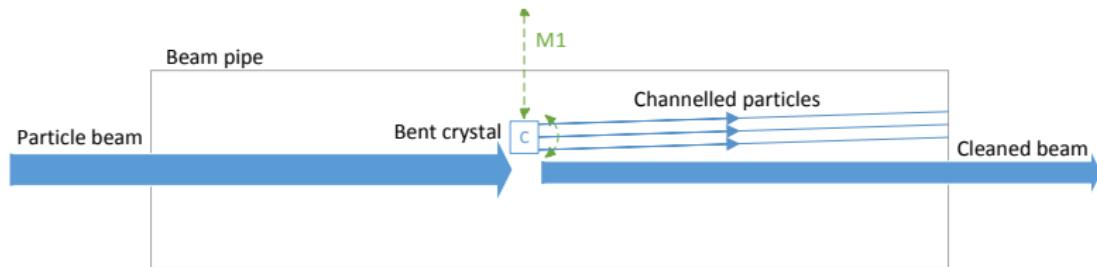
# Collimation

Collimators used at CERN. Source: [2].



# Crystal Collimation

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

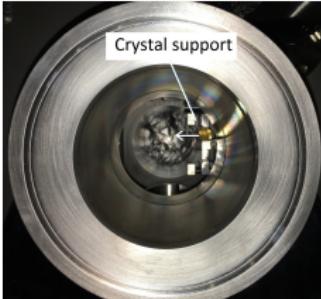


Implies in a more efficient cleaning, a less complex system and a reduction of the machine impedance.

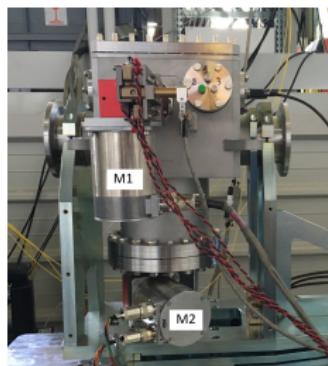
# Crystal Collimator



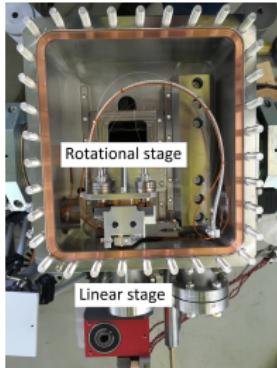
Giving access



Insertion of crystal



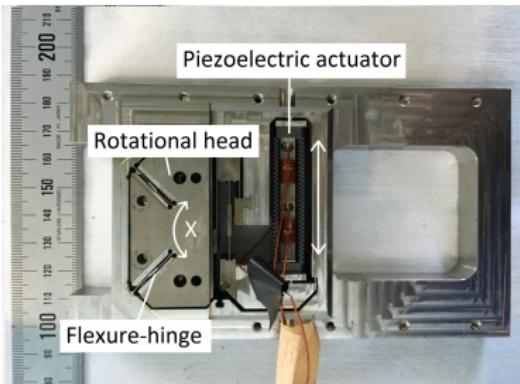
Side view



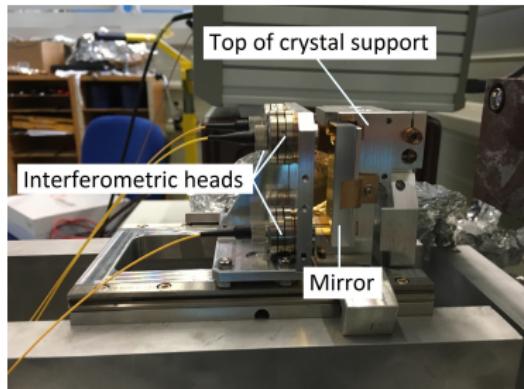
Top view

# Rotational Stage

- Monolithic structure to avoid sliding parts
- Piezoelectric stack actuator
- Displacement range:  $30 \mu\text{m} \implies 20 \text{ mrad}$



Rotational stage



Interferometric system

# Project Overview

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## Purpose and Goal

**Identify applicable control approaches to improve the overall tracking performance of the rotational stage.**

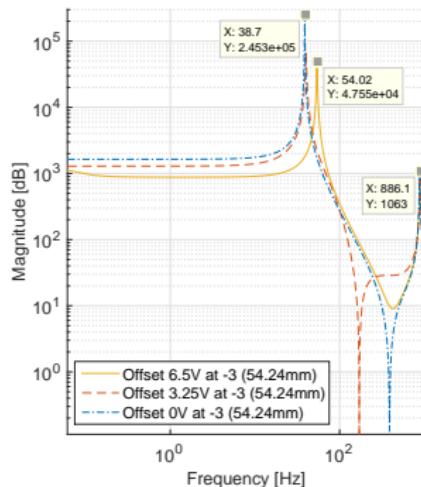
The **rotational stage** should:

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

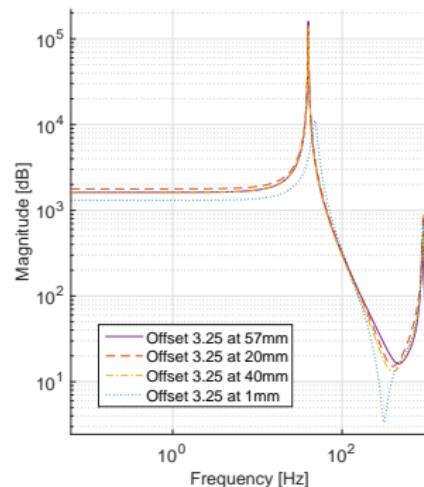
One approach had already been developed.

# 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.



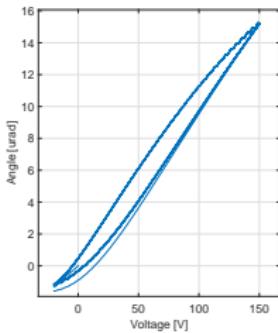
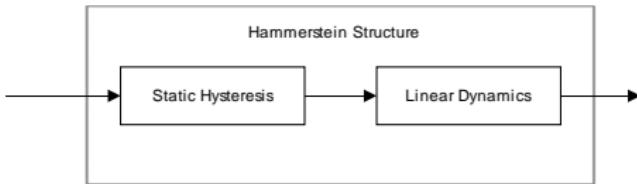
Model at different angles



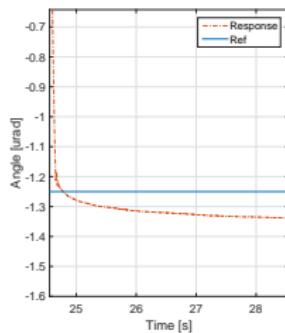
Model at different linear positions

# Present Control Approach

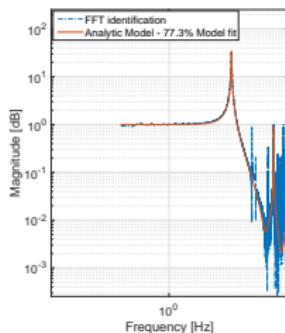
- Hammerstein structure - Model the rotational stage
- Hysteresis effect - Modeled by a Maxwell slip model
- Creep effect - Efficiently eliminated in closed loop



Hysteresis



Creep

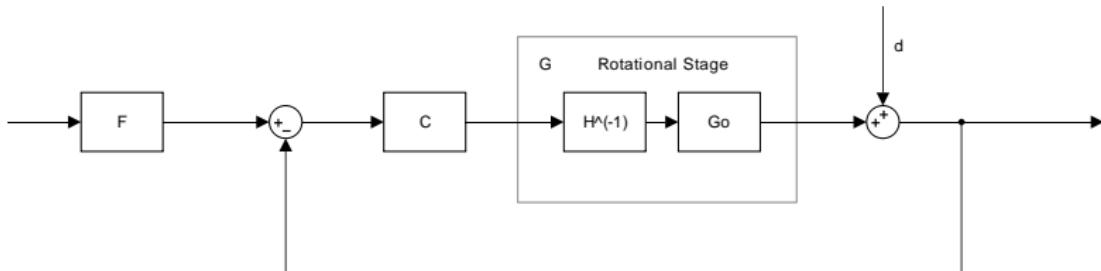


Linear Model

# Present Control Approach

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

- PID - for stability
- Notch filter - to cancel high frequency oscillations
- Lead filter - to increase the phase margin
- Prefilter - to increase closed loop bandwidth



## **Approaches and Simulation Results**

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# 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.

System model

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

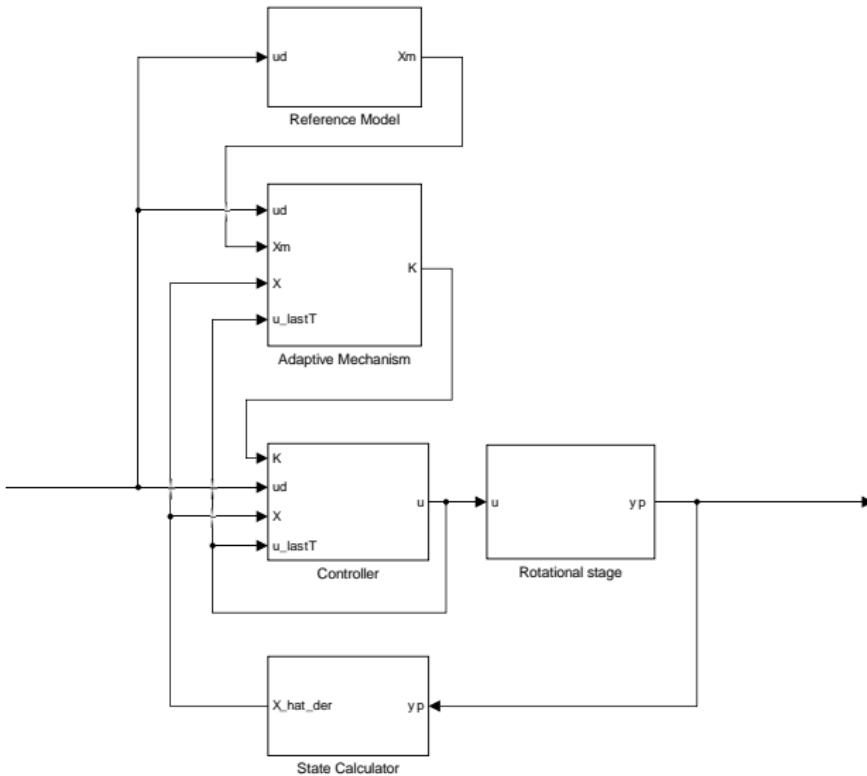
Reference model

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

Final control law

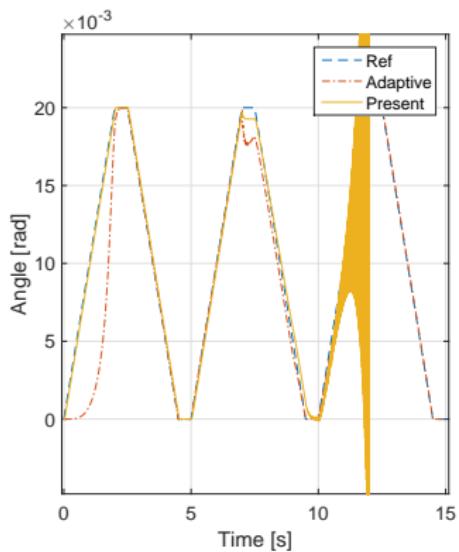
$$u(t) = k_0 u_d(t) + (k_1 + k_3 \alpha_0) x(t) + (k_2 + k_3 \alpha_1) \dot{x}(t) + k_3 \ddot{x}(t) - k_3 \beta_0 u(t - T_s)$$

# Model Reference Adaptive Controller

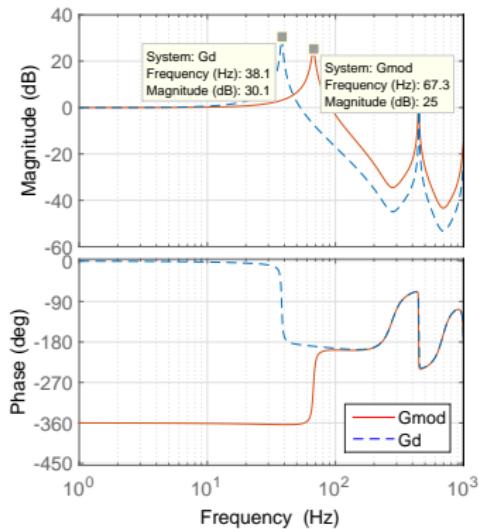


# Model Reference Adaptive Controller

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



Periodic response

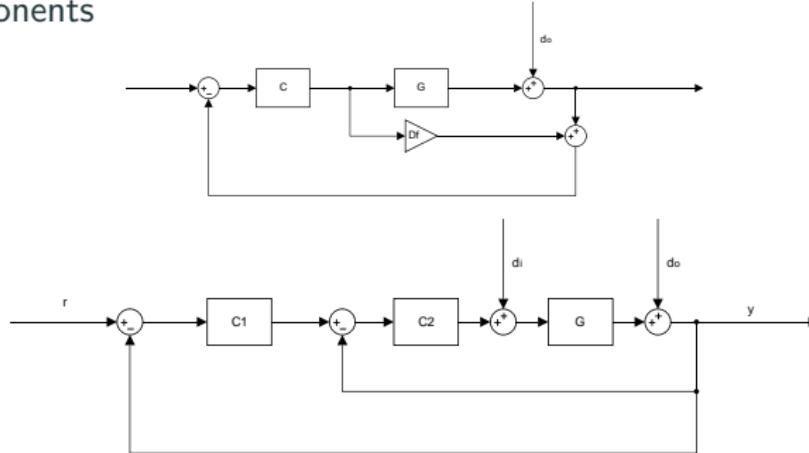


Model change

# Integral Resonance Control

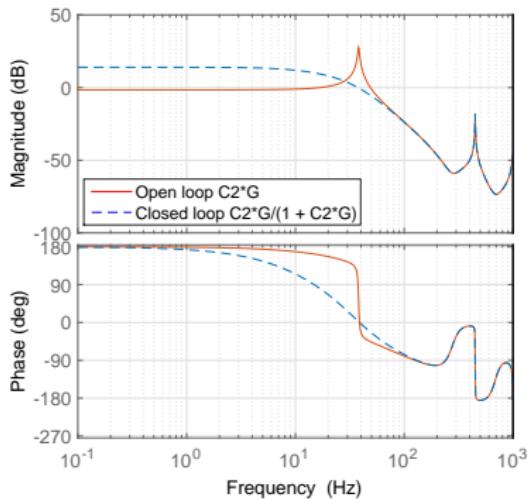
Idea: Increase the yaw angle tracking accuracy.

- Uses a constant negative feed forward to damp out the first resonance peak
- Integral controller is used for inner loop stability
- Simplified with  $C_2(s) = \frac{C(s)}{1+C(s)D_f}$
- C1 is designed for reference tracking and attenuating high frequency components

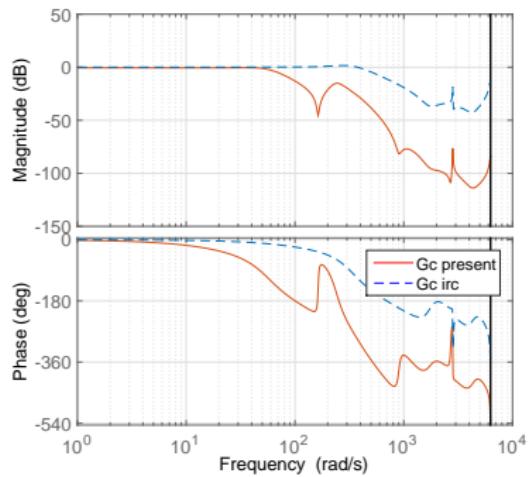


# Integral Resonance Control

- Effect of IRC-damping.
- Increased closed loop bandwidth from 11 Hz to 73 Hz implying in a better tracking performance.



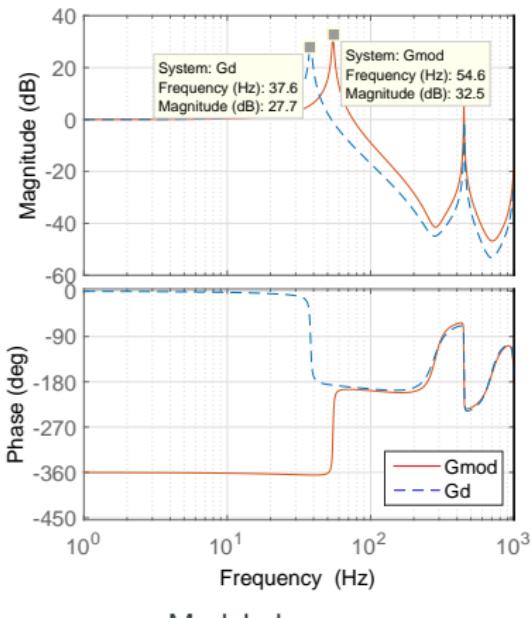
IRC-damping



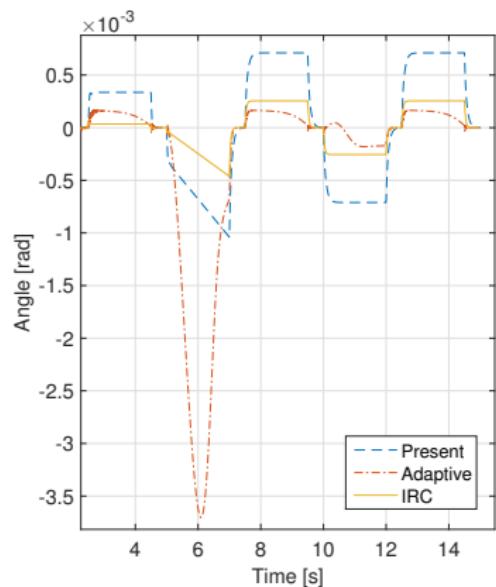
Closed loop bandwidth

# Tracking performance comparison

Tracking error from periodic input with model parameter drift increased linearly from  $t = 5$  s to  $t = 7$  s.



Model change



Tracking error

# 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

**Repetitive Feedforward Disturbance Cancellation:** 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
- Not affecting the closed loop system

# Repetitive Feedforward Disturbance Cancellation

The state space system and observer is given as

$$\dot{\mathbf{x}}(t) = \mathbf{A}_c \mathbf{x}(t) + \mathbf{B}_c(u(t) + d_o(t)) \quad (1a)$$

$$y(t) = \mathbf{C}_c \mathbf{x}(t) \quad (1b)$$

$$\dot{\mathbf{x}}_d(t) = \mathbf{A}_d \mathbf{x}_d(t) \quad (1c)$$

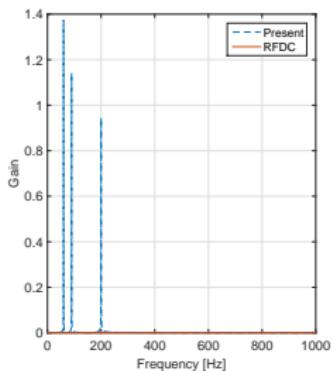
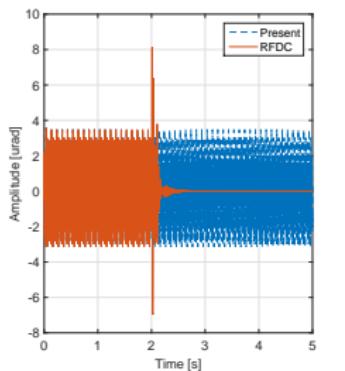
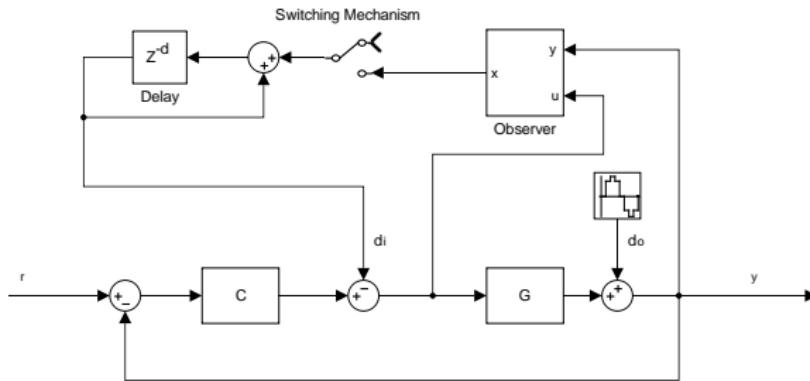
$$d_o(t) = \mathbf{C}_d \mathbf{x}_d(t) \quad (1d)$$

$$\frac{1}{w} \sin(wt) \implies \mathbf{A}_d = \begin{bmatrix} 0 & 1 \\ -w^2 & 0 \end{bmatrix} \quad \mathbf{C}_d = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

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

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{zs} & \mathbf{C}_{zd}\mathbf{B}_{zs} \\ \mathbf{0} & \mathbf{A}_{zd} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} \mathbf{B}_{zs} \\ \mathbf{0} \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} \mathbf{C}_{zs} & \mathbf{0} \end{bmatrix}$$

# Repetitive Feedforward Disturbance Cancellation



## **Implementation**

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# Setup

- Implementation in LabVIEW
- Deployed on a National Instruments PXI (2kHz)
- Shaker



Shaker

Main | Offsets | Protection | filter 1 | filter 2 | filter 3 | filter 4 | Hysteresis Compensator | Harmonic Cancellation

Harmonic cancellation parameters

Calculate Kalman gain      Observer done (green light)

Cancellation On/Off      Ready to apply (green light)

Apply Cancellation

Selected Frequencies: 0, 50, 200, 0

Start saving disturbance: 5      Save duration: 0, 0.02

Q: 0, 0, 1E-5      R: 0, 1  
G: 0, 0, 1      Ts: 0, 0.0005

System State-Space Model

A	-1.09	0.56	1.07	B	16	0
0	2	0	0	0	0	0
0	0	1	0	0	0	0
0	0	0	0	0	0	0

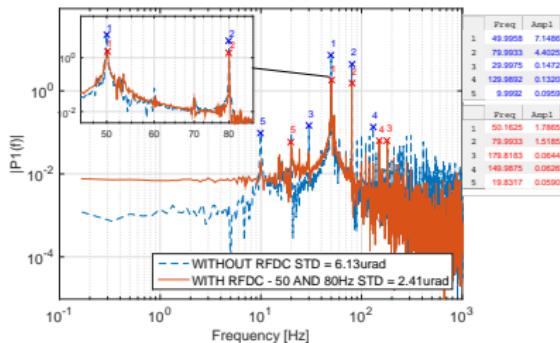
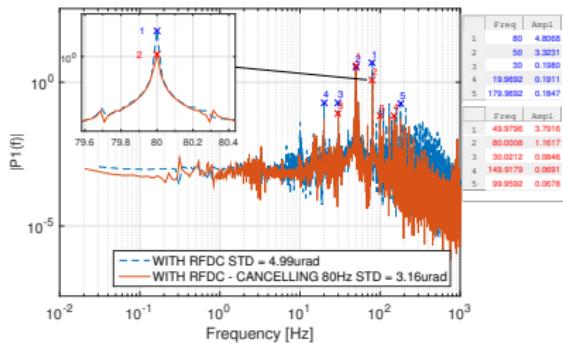
Observer State-Space Model

A	-1.09	0.56	1.07	B	16	0
0	-0	-0.01	-0.01	0	0	0.01
0	0	1	-0	0	0	0
0	0	0	0	0	0	0

GUI

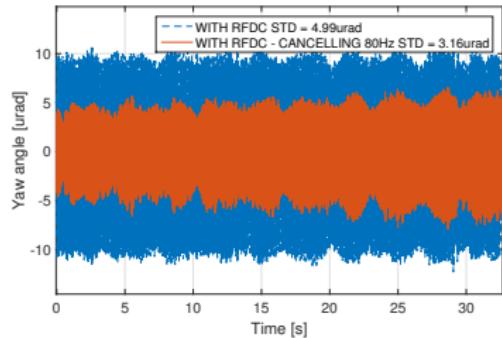
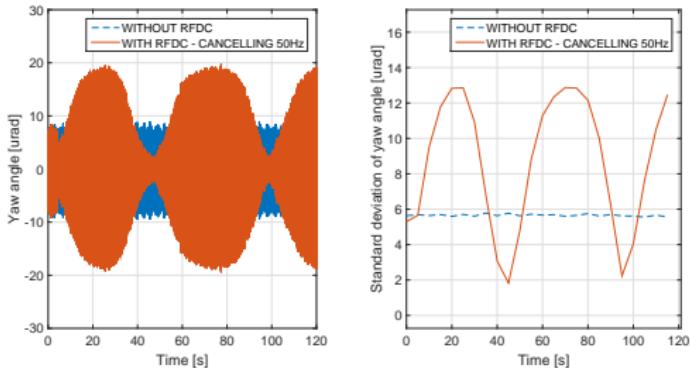
# Cancellation verification

- (Single disturbance) 80 Hz (76%)
- (Multiple disturbances) 50Hz (75%) 80Hz (66%)



# Beat effect

Cancellation performance varies, esp. for cancellation close to the resonance.



## **Conclusion**

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# Summary of Findings

## IRC

- Can be used to efficiently increase the closed loop bandwidth
- No direct information of the first resonance peak
- Tradeoff: Tracking performance - Controller robustness

## Adaptive

- Can be used to adapt to large model changes and thereby prevent instability
- Tradeoff: Adaption time - Stability

## RFDC

- Can be used to efficiently damp out known harmonic oscillations (even outside the closed loop bandwidth)
- Suffers from beat effect. Less obvious for generated disturbance
- Tradeoff: Convergence time - Cancellation effectiveness

# Future Work

## IRC + Adaptive + RFDC

- Combination of two or three approaches
- Increasing tracking performance
- Adaptive to long term changes such as temperature and radiation

## Improvement of the RFDC

- More investigation in the cancellation performance.
- Beat effect solutions:
  - Increase observation time
  - Use a few elements to synchronize the replicated signal.

## Improvement of the mechanical design

- CERN is now developing a new rotational stage
- Applies the force directly to the rotational head
- More stiff  $\implies$  higher bandwidth, easier to design a sufficient controller

**Thank you!**

# Model Reference Adaptive Controller

$$e(t) = x(t) - x_m(t)$$

$$\ddot{e}(t) + a_1 \dot{e}(t) + a_0 e(t) = (a_1 - \alpha_1) \dot{x}(t) + (a_0 - \alpha_0) x(t) - b_0 u_d(t) - \beta_0 u(t) + \hat{f}(t)$$

$$\dot{\mathbf{E}} = \mathbf{A}\mathbf{E} + \beta_0 \mathbf{B}u + \Delta$$

where

$$\mathbf{E} = \begin{bmatrix} e \\ \dot{e} \end{bmatrix}, \mathbf{A} = \begin{bmatrix} 0 & 1 \\ -a_0 & -a_1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \Delta = \begin{bmatrix} 0 \\ \delta \end{bmatrix}$$

$$\text{with } \delta = (a_1 - \alpha_1) \dot{x}(t) + (a_0 - \alpha_0) x(t) - b_0 u_d(t) + \hat{f}(t).$$

If all eigenvalues of  $\mathbf{A}$  have negative real parts, then  $\mathbf{E}$  will tend to zero as  $t \rightarrow \infty$ , i.e. the system is asymptotically stable. According to Lyapunov theory, for each positive-semidefinite matrix  $\mathbf{Q}$  there exists one positive-semidefinite matrix  $\mathbf{P}$  which solves (2).

# Model Reference Adaptive Controller

$$\mathbf{A}^T \mathbf{P} + \mathbf{P} \mathbf{A} = -\mathbf{Q}$$

With the auxiliary item  $\hat{e} = \mathbf{E}^T \mathbf{P} \mathbf{B}$ , the adaptive laws are given by

$$u = k_0 u_d + k_1 x + k_2 \dot{x} + k_3 \hat{f}$$

where the control law parameters are calculated as outlined below.

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

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

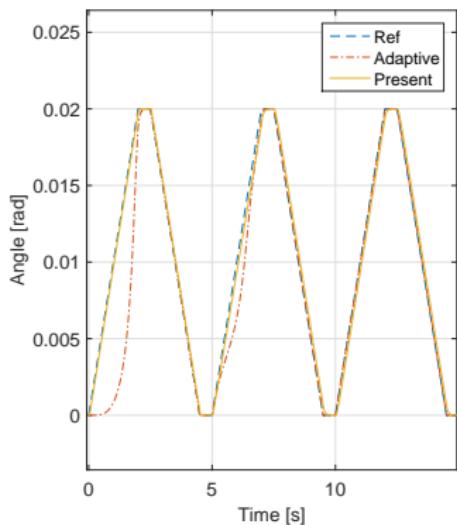
$$\dot{k}_2 = -\eta_2 \hat{e} \dot{x}$$

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

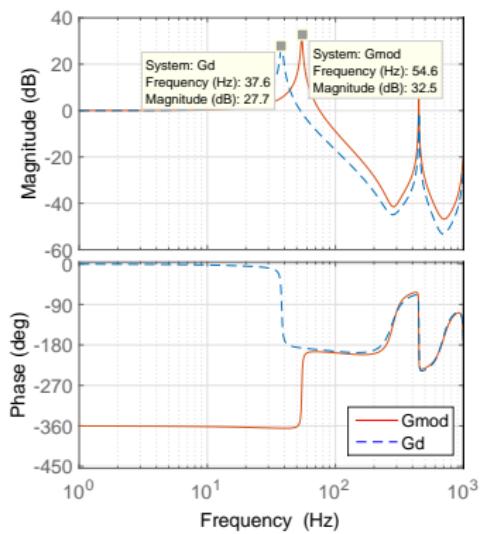
$$u(t) = k_0 u_d(t) + (k_1 + k_3 \alpha_0) x(t) + (k_2 + k_3 \alpha_1) \dot{x}(t) + k_3 \ddot{x}(t) - k_3 \beta_0 u(t - T_s)$$

# Model Reference Adaptive Controller

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



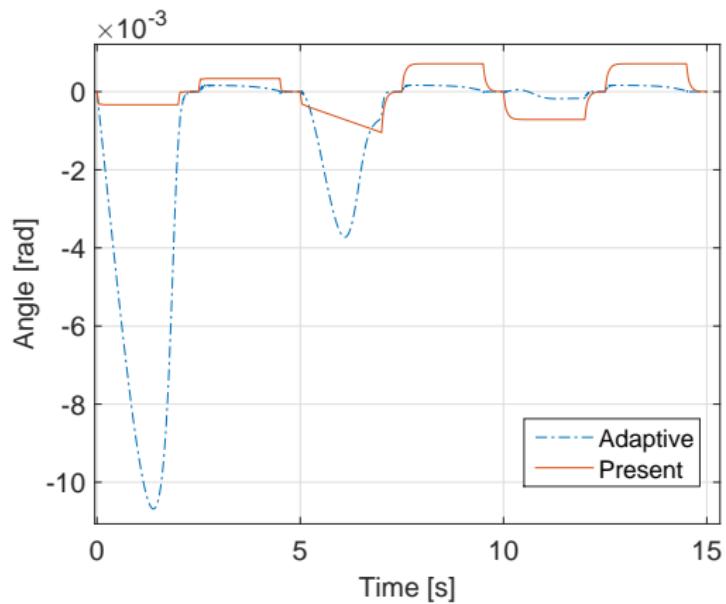
Periodic response



Model change

# Model Reference Adaptive Controller

Tracking error

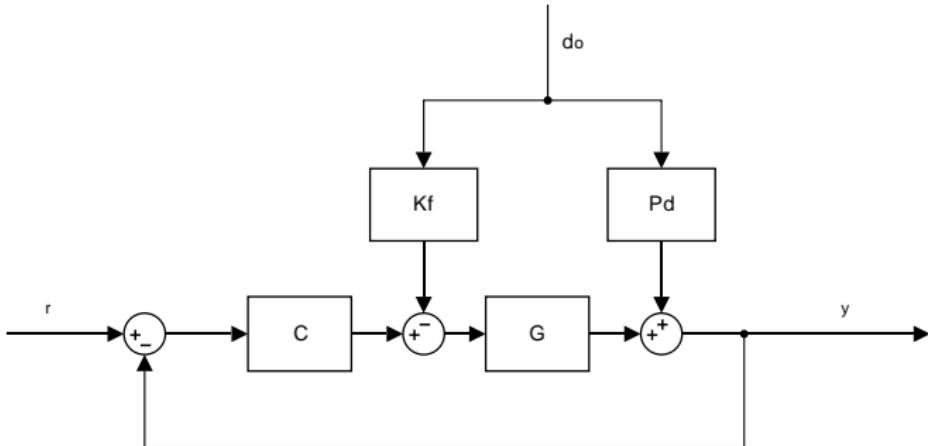


## Feedforward Disturbance Cancellation

**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

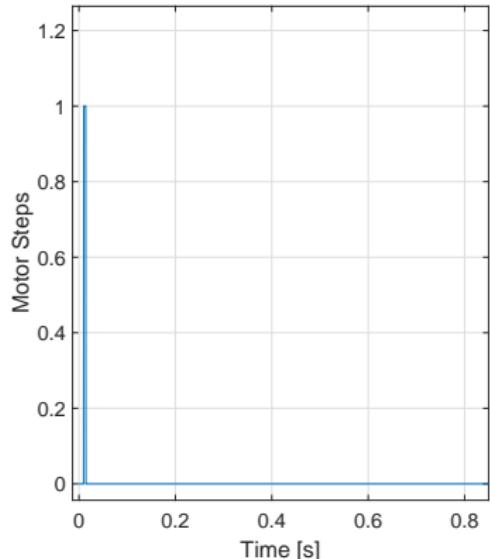


$$Y(s) = \frac{C(s)G(s)}{1 + C(s)G(s)}R(s) + \frac{P_d(s) - K_f(s)G(s)}{1 + C(s)G(s)}D_0(s)$$

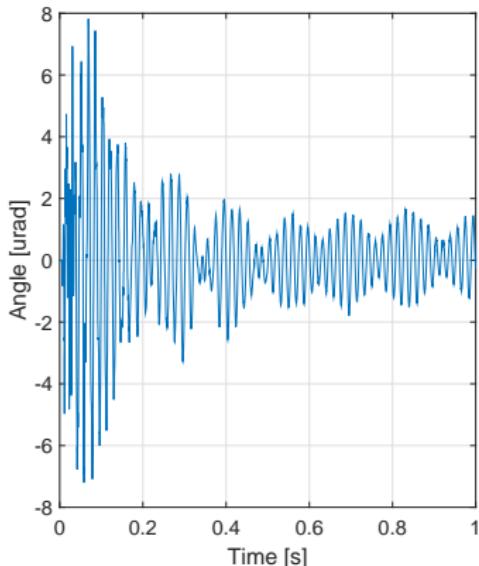
Ideal choice:  $K_f(s) = P_d(s)/G(s)$

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

# Feedforward Disturbance Cancellation

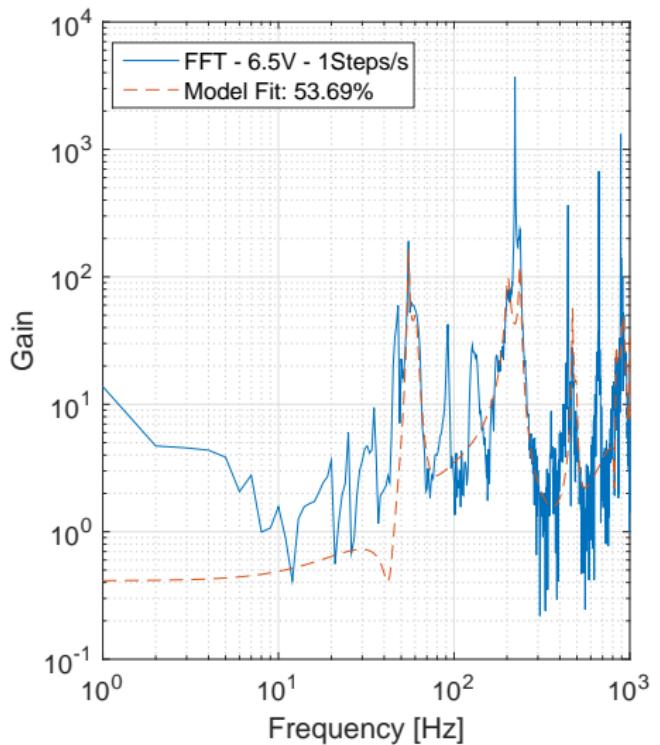


Impulse used as input signal

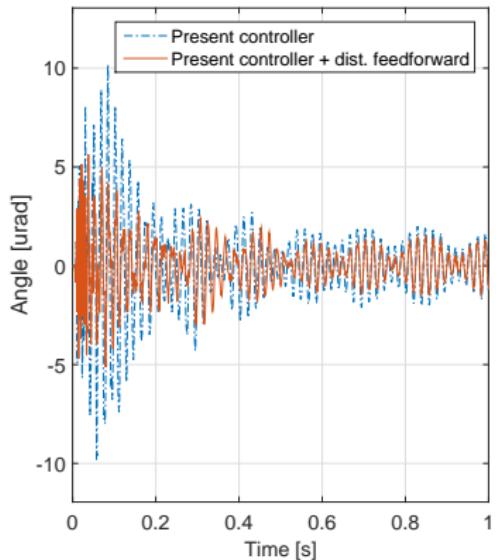


Mean of impulse responses

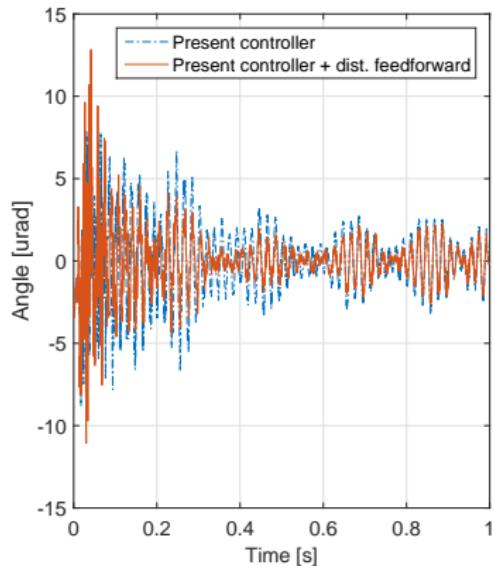
# Feedforward Disturbance Cancellation



# Feedforward Disturbance Cancellation



Mean as disturbance



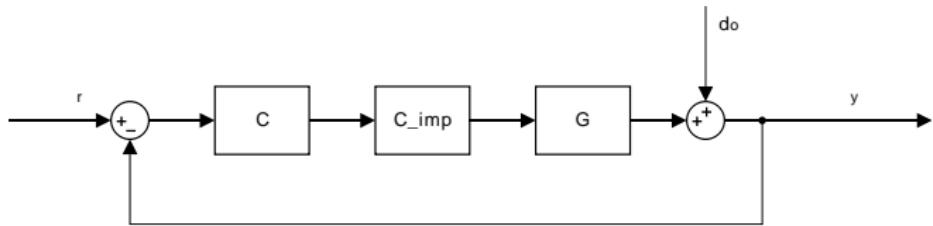
Original acquired signal as disturbance

## Cancellation with Internal Model Principle

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

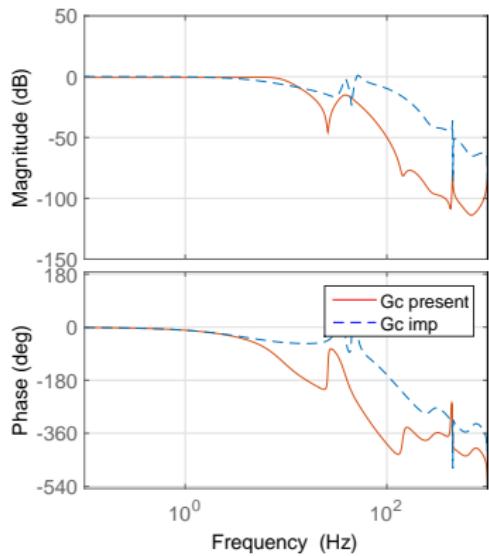
- Asymptotically reject the modeled disturbance
- Affecting the closed loop system

# Cancellation with Internal Model Principle

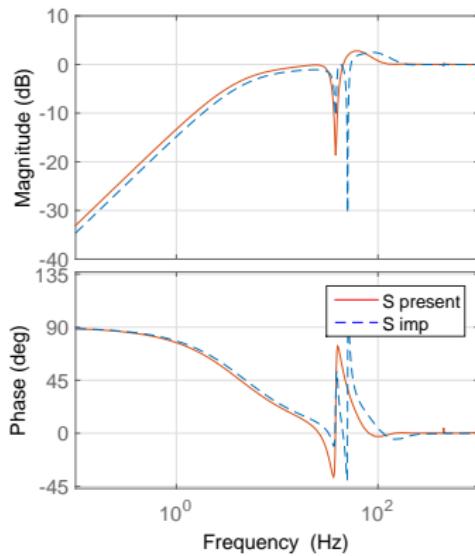


The generating polynomial  $\Gamma(s) = f(0, s)/D(s)$ .  
 $C_t(s) = P(s)/(\Gamma(s)\bar{L}(s))$ .

# Cancellation with Internal Model Principle

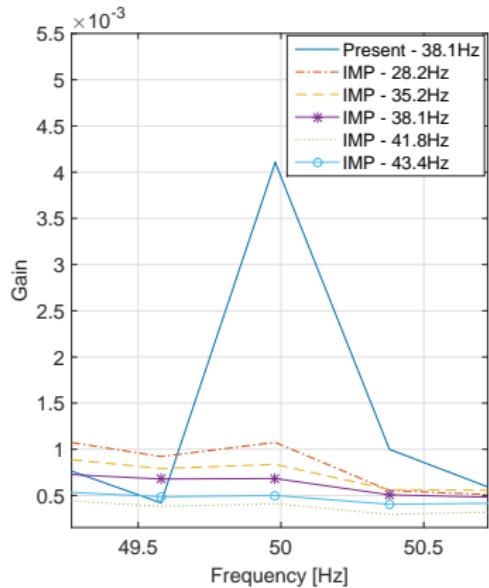


Closed loop system

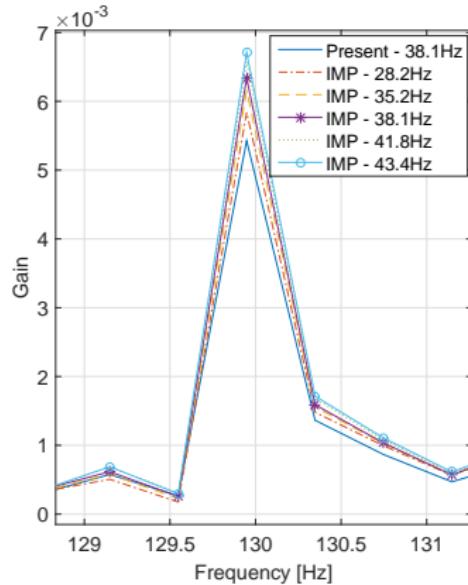


Sensitivity function

# Cancellation with Internal Model Principle



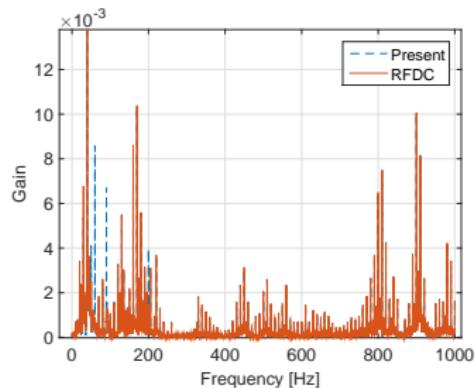
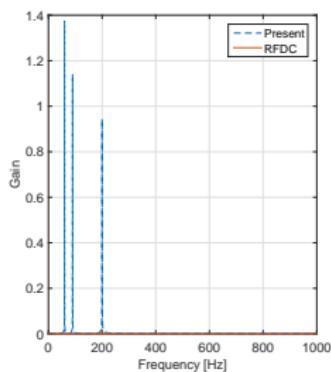
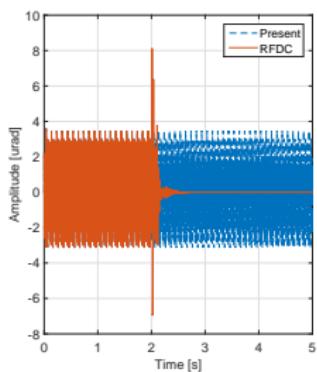
Attenuation of selected frequency



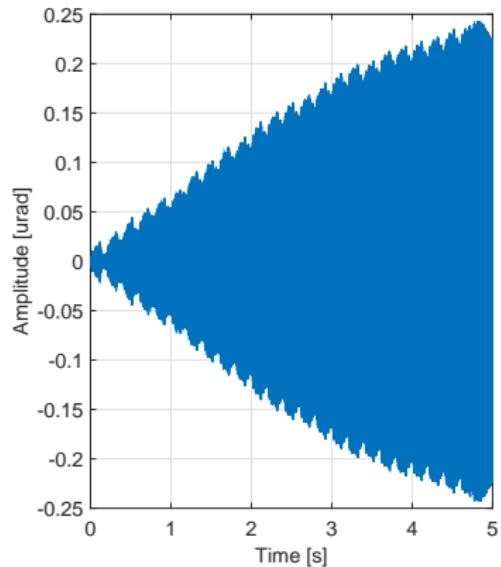
Impact on 130 Hz component

# Repetitive Feedforward Disturbance Cancellation

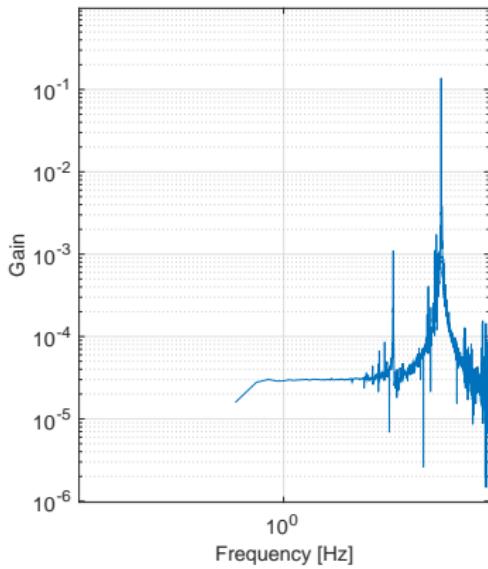
- Cancellation of the 60, 90 and the 200 Hz
- Real acquired data used in simulations
- Not affecting other frequency components



# Repetitive Feedforward Disturbance Cancellation

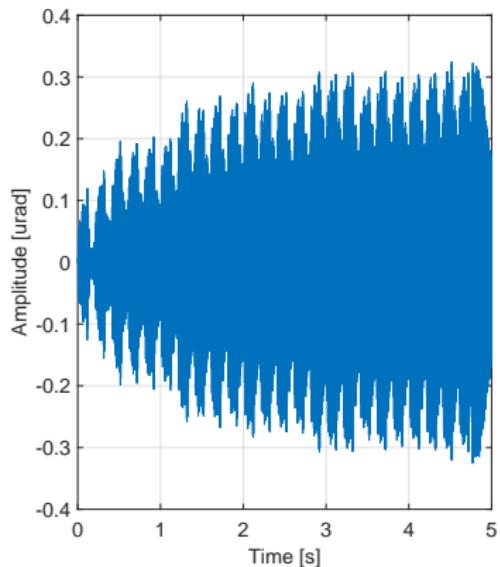


Time domain

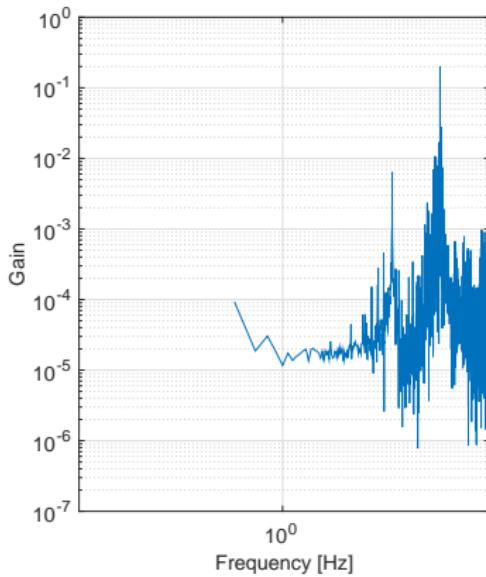


FFT

# Repetitive Feedforward Disturbance Cancellation



Time domain



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 $\sigma$ -[mrads]	0.29	0.03	0.11
4	Tracking error with model errors (model's 1st resonance at 22.0Hz), $\sigma$ -[mrads]	$\infty$	0.03	0.21
5	Tracking error with model errors (model's 1st resonance at 67.2Hz), $\sigma$ -[mrads]	$\infty$	0.03	0.11
6	Tracking error with model errors (model's 1st resonance at 17.6Hz), $\sigma$ -[mrads]	$\infty$	$\infty$	0.47
7	Tracking error with model errors (model's 1st resonance at 77.7Hz), $\sigma$ -[mrads]	$\infty$	$\infty$	0.11

# Comparison

No	Aspect	Present	IRC	MRACPE
8	Output disturbance rejection, settling time (1%) [ms]	8	25	260
9	Input/Output disturbance rejection, $\sigma$ -[μrad ]	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.

# References for Graphics I

-  C. De Melis.  
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Available at <https://cds.cern.ch/record/2197559>.
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**opac hector garcia morales - lhc collimation system optimization, 2015.**  
Available at <https://www.youtube.com/watch?v=h2-ocLjUhTU>.

All other references are listed in the Master's Thesis report.