Application of Active Disturbance Rejection Control in Superconducting Radio Frequency Cavities

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Outline

- Previous Results on Microphonics Mitigation
- More on Active Disturbance Rejection Control (ADRC)
- ADRC Applications at FRIB/NSCL
  - Beam Loading
  - FPGA Implementation
  - Tuner Control
  - ReA3 Vibration Test
First Application of ADRC in SFR Cavities

- Application of ADRC at NSCL
  - Spring 2010
  - Narrow bandwidth and sensitive to vibrations
  - ReA3 is on the balcony and the vibration is severe
Demonstrated the effectiveness of ADRC [Vincent, 2011]

- Two times improvement in simulation (top)
- Four times improvement in tests (bottom)
- Running on ReA3 since Jan. 2011
Better Decoupling

**Simulation**

**Test**

**Amplitude Set-point Change**
- Simulation: PID vs. ADRC
- Test: PID vs. ADRC

**Phase Set-point Change**
- Simulation: PID vs. ADRC
- Test: PID vs. ADRC

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Application of ADRC in SRF Cavities
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Active Disturbance Rejection Control

- Proposed by Prof. Han in 1998 [Han 2009]
  - Treat external disturbance and system uncertainty as the *total disturbance*
  - Estimation the total disturbance using an extended state observer (ESO)
  - Cancel it in the controller

- Other Similar Methods
  - Unknown Input Observer
  - Disturbance Observer
  - Perturbation Observer
    (only deal with external disturbance)
ADRC Formulation - A Simple Example

\[ m \ddot{y} = F + g(y, \dot{y}, t) + w(t) \]

- **Internal Uncertainty**
- **External Disturbance**

\[ f(y, \dot{y}, w, t) = \frac{g(y, \dot{y}, t) + w(t)}{b} \]

\[ u = \frac{-\hat{f} + u_0}{b} \]

\[ \ddot{y} = u_0 + \left( f - \hat{f} \right) \approx u_0 \]

\[ u_0 = k_p e + k_d \dot{e} \]

Simple Controller

Total Disturbance

Disturbance Cancellation

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SRF Cavity Model

- **Parallel RLC Circuit Model**

\[
\frac{d^2 \vec{V}_c}{dt^2} + \frac{\omega_0}{Q} \frac{d \vec{V}_c}{dt} + \omega_0^2 \vec{V}_c = \frac{R \omega_0}{Q} \frac{d I_g}{dt}
\]

\[
\omega_0 = \frac{1}{\sqrt{LC}} \quad Q = R \sqrt{C/L}
\]

- **Approximation**

\[
\dot{V}_{cl} + \omega_{1/2} V_{cl} + \Delta \omega V_{cQ} = \omega_{1/2} V_{gI}
\]

\[
\dot{V}_{cQ} + \omega_{1/2} V_{cQ} - \Delta \omega V_{cl} = \omega_{1/2} V_{gQ}
\]

\[
\begin{cases} 
  I = A \cos P \\
  Q = A \sin P
\end{cases}
\]
ADRC Design for SRF Cavity

\[
\begin{align*}
\dot{V}_{cI} + \omega_{1/2} V_{cI} + \Delta \omega V_{cQ} &= \omega_{1/2} V_{gI} \\
\dot{V}_{cQ} + \omega_{1/2} V_{cQ} - \Delta \omega V_{cI} &= \omega_{1/2} V_{gQ}
\end{align*}
\]

- **Algorithm**
  - **System**
    \[ \dot{y} = f(y, w, t) + bu \]
  - **Observer**
    \[ \begin{align*}
    \dot{x}_1 &= \dot{x}_2 + \hat{b}u + l_1(y - \hat{x}_1) \\
    \dot{x}_2 &= l_2(y - \hat{x}_1) \\
    u &= (k_1(r - y) - \hat{x}_2) / \hat{b}
    \end{align*} \]
  - **Controller**
Disturbances in SRF Cavities

- **Microphonics**
  - Ground vibration;
  - Pumps: Helium pump, vacuum pump, etc.

- **Lorentz Force**

- **Beam Dynamics**
  - Beam loading;
  - Beam current variation.

- **Others**
  - Hysteresis in piezo tuner;
  - Non-linearity in solid state amplifier.
Beam Loading [Zheng 2012]

- Simulation Model
Results under Beam Loading

- Amplitude Response

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Cavity Amplitude Fluctuation due to Beam Loading

- $0.28\%$
- $0.039\%$

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Results under Beam Loading

- Phase Response

Cavity Phase Fluctuation due to Beam Loading

- Time (s)
  - Cavity Phase (°)
    - X: 1.5
      - Y: -29.91
    - X: 1.001
      - Y: -29.99
    - X: 1
      - Y: -30.01
    - X: 0.5003
      - Y: -30.1
    - X: 0.4
      - Y: -30.15
To increase the sampling rate

- Potential performance improvement
  - Observer bandwidth can be further increased;

- Expands the working range of the SEL
  - 1/12 of the sampling rate [Zhao 2011];
  - Currently around 4 KHz (50 KHz in DSP);

No processor planned in LLRF controller (long term)

- ADRC algorithm has to go into the firmware;
Simulation Results

- A Comparison between Fixed-point and Floating-point Algorithms

![Graph showing Amplitude and Phase Response](image-url)

- Simulation Results

![Graph showing Set-point and Algorithm Comparison](image-url)
Hardware Test Verification

- LLRF Controller PED 1

**FRIB Specs:**

Amplitude (RMS): <0.25%

Phase (RMS): <0.25 degrees

**PDF of Cavity Amplitude Deviation**

**PDF of Cavity Phase Deviation**

- $\sigma = 0.0084\%$
- $\sigma = 0.11^\circ$
### Fast Piezoelectric Tuner

- Hysteresis compensation [Goforth 2012]
Simulation Results

Hysteresis Input/Output Relation

- Hysteresis
- Ideal Linear

FFT of the Signals

- Reference
- System Output
- Hysteresis Input
- Hysteresis Output

Residual nonlinear effect
ReA3 Vibration Test

- Original Measurement

RMS Cavity Amplitude Deviation ($\Delta f=0.5$ Hz)

- RMS Cavity Phase Deviation ($\Delta f=0.5$ Hz)
Disturbance Rejection Characteristics of the ADRC Controller

Bode Diagram

cavity half bandwidth = 35 Hz

Magnitude (dB)

Phase (deg)

Frequency (Hz)

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### RMS Cavity Amplitude Deviation ($\Delta f=0.5$ Hz)

- X: 29.5, Y: 0.00547
- X: 447.5, Y: 0.01361
- X: 895.5, Y: 0.005769

### RMS Cavity Phase Deviation ($\Delta f=0.5$ Hz)

- X: 29.5, Y: 0.0223
- X: 447.5, Y: 0.04675
- X: 895.5, Y: 0.0009569

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### Table of Data

<table>
<thead>
<tr>
<th>Pumps</th>
<th>Controller</th>
<th>Cavities</th>
<th>Acceleration</th>
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<td>L077</td>
<td>L082</td>
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<td>3000 600</td>
<td>0.074 0.09</td>
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Questions
Thanks for your attention!