Active Suppression of Microphonics Detuning in High $Q_L$ Cavities

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Overview

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Introduction

- **Energy Recovery Linacs** and some **Free Electron Lasers** require SRF cryomodules with low to zero beam loading.

- Almost all RF power is used to maintain stable field.

- We can operate using high loaded quality factors (~ $10^8$) and reduce average power requirements.

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European XFEL
The peak detuning of the cavity must be less than 54 Hz in order to sustain a cavity voltage of 6 MV using a power amplifier capable of delivering 5 kW.
Mitigation of vibration sources is the preferred method of reducing peak microphonics detuning, but having an active control system is also necessary!

As an example, the CBETA Main Linac 7 cell cavities are attached to a tuner based on the Saclay I design with added fast actuators.

Observations:

1. Phase response is almost 0° up to 30 Hz, this makes it ideal for proportional integral feedback control.
2. For higher frequencies of the phase response is very noisy, especially for un-stiffened cavities.
3. The mechanical eigenmodes of stiffened cavity starts at a higher frequency and in general has a smaller response amplitude.
Our microphonics lines are fairly narrowband.

**Assumptions:**
1. The detuning can be described as slowly varying sine waves.
2. The tuner response around the relevant frequency can be treated as a constant complex number.

We can compensate for narrowband microphonics detuning by applying a sum of sine waves on the actuator. (**Narrowband Active Noise Control (ANC)**)

**Problem:** Adjust $I_m$ and $Q_m$ to modulate the carriers at frequencies $\omega_m$ to reduce detuning.

**Fixed Parameters:** Learning Rate (gain) $\mu_m$ and Controller Phase $\phi_m$
Stability

The ANC algorithm is a feedback controller.

![Feedback Controller Diagram]

The controller phase $\varphi_m$ and the gain $\mu_m$ determine the stability of the controller.

Tuner resonances also affect stability.

We use a FIR low pass filter to suppress resonances above 200 Hz.
How to choose controller parameters?

Instead of depending on transfer function measurements, use Least Mean Square (LMS) to determine optimum controller phase in-situ and introduce $\eta_m$

The modified ANC algorithm estimates the phases and keeps them in the stable region even if the transfer function changes.
The modified narrowband ANC was tested on some cavities of the main linac.

### Results

The algorithm is effective and stable over hours of operation! No mechanical coupling with neighboring cavities because of bellows in our cryomodule.

| Run Description                                           | Peak Detuning (Hz) | RMS Detuning (Hz) |
|-----------------------------------------------------------|--------------------|-------------------|
|                                                           | ANC Off | ANC On | ANC Off | ANC On |
| Cavity 1 with JT and precool static                       | 78      | 45     | 13.6    | 9.1    |
| Cavity 3 with JT and precool static                       | 100     | 57     | 20.8    | 11.7   |
| Cavity 3 with JT and precool static and 5 K valve modified| 50      | 22     | 10.7    | 4.6    |
| Cavity 4 with JT and precool static                       | 17      | 19     | 4.4     | 2.4    |
| Cavity 6 in original configuration                        | 30      | 15     | 6.4     | 3.4    |
Conclusions

• High Loaded Quality Factors
  Many modern accelerators with low beam loading are pushing the limits on loaded quality factors up to $10^8$. While reducing average power requirements, this makes the system very sensitive to microphonics.

• Microphonics Suppression
  Passive mitigation of vibration sources is the method of choice. In addition, we use fast tuners to achieve active microphonics compensation.

• Narrowband Active Noise Control
  With narrowband microphonics, we can use the ANC feedback control system whose stability is determined by the controller gains and phases.

• Phase Adaptation
  We introduced phase adaptation based on the Least Mean Square approach, which makes ANC more robust towards changes in the tuner response.

• Results
  We demonstrated stable and effective operation of the algorithm with beam over multiple hours with almost a factor of 2 reduction in the peak detuning on both stiffened and un-stiffened cavities.
We have reached single pass energy recovery up to 8 µA and measured a net energy balance of 99.6 ± 0.1 %
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Thank you!
Appendix 1: Cryogenic System

Three subsystems:
1. **40 K / 80 K**
   Thermal shield, input couplers, HOM loads.
2. **4.5 K / 6.5 K**
   Input couplers, beam pipe.
3. **2 K / 1.8 K**
   Cavities.

2 K liquid Helium system controlled by:
1. **Pneumatic Joule-Thomson (JT) and precool valve.**
   Controls amount of LHe entering the 2 K 2 phase pipe.
2. **2 K 2 Phase heater**
   Adds heat load if necessary.
3. **Pump Skid**
   Controls vapor pressure in 2 K 2 phase pipe supplying to the Helium vessels thus controlling bath temperature.
Appendix 2: Current Microphonics

- Detuning (Hz)

- Vibration Frequency (Hz)

- Probability Density (Hz$^{-1}$)

- RMS Detuning (Hz)

Detuning vs. Probability Density

Vibration Frequency vs. RMS Detuning
Appendix 3: Theoretical Bounds

(a) Attenuation vs. $\mu_m$

(b) $\phi_m^{opt}$ vs. $\mu_m$

(c) Attenuation vs. $Q_v$

(d) $\phi_m^{opt}$ vs. $Q_v$
The Cornell LLRF incorporates a FPGA for field control in Generator Driven Resonance (GDR) mode which operates on the 12.5 MHz IF signals.

The field probe and forward power signals are used to calculate detuning.

A DSP chip incorporates the modified ANC, proportional-integral and the LFD controller running at 10 kHz.