ADRC CONTROL FOR BEAM LOADING AND MICROPHONICS *

Z. Zheng# (FRIB, East Lansing, Michigan; TUB, Beijing)
Z. Liu, J. Wei, S. Zhao, Y. Zhang (FRIB, East Lansing 48824, Michigan, USA)

Abstract

Superconducting RF (SRF) cavities are subject to many disturbances such as beam loading and microphonics. Although we implemented Proportional Integral (PI) control and Active Disturbance Rejection Control (ADRC) in the Low Level RF (LLRF) system at FRIB to stabilize the RF field, the control loop gains are inadequate in the presence of beam loading and microphonics. An improved scheme is proposed and simulated with much higher gains are achieved. The feasibility to include piezo tuner in ADRC and PI circuit is also presented in this paper.

INTRODUCTION

For a SRF cavity, there exist many disturbances, either external or self-induced, in which beam loading and microphonics are two most important ones. While beam loading disturbs the cavity voltage and RF phase with beam induced voltage, microphonics detunes cavity by mechanical perturbations. To reject the disturbances, PI control strategy and ADRC method have been considered. PI handles disturbances in a passive way, reacting to tracking errors caused by the disturbances, while ADRC rejects the disturbances actively by estimating the disturbances directly.

In the original LLRF system of FRIB cavities, both PI and ADRC solutions are implemented to control the amplitude and phase separately, because it was assumed that independent amplitude and phase control will benefit more to operation. Simulation shows that such a scheme presents potential difficulties in phase control, with both ADRC and PI, where the loop gain can be inadequate to reject microphonics. Figure 1 shows the phase fluctuation of ADRC exceeds the cavity phase stability limit of 0.5 degree. PI control performs worse than ADRC with much larger phase and amplitude fluctuations with separated phase and amplitude controllers.

According to SNS LLRF control experience [1], we proposed a new scheme to process and control the cavity voltage as a vector instead of separating amplitude and phase. Section 1 explains the new model of ADRC control. Section 2 shows the comparison of ADRC and PI with the new scheme, from which one can see the stable loop gain increased significantly and rejected beam loading and microphonics effectively. Section 3 discusses the feasibility to reject microphonics by a piezo-tuner.

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#zhzheng@msu.edu

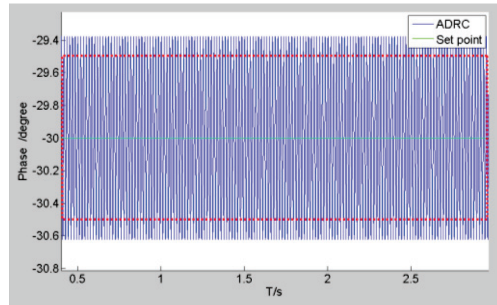

Figure 1: Phase fluctuation to reject microphonics by the original ADRC scheme. The red line marks the fluctuation limit due to stability concern of cavity phase. Microphonics amplitude is assumed to be 20Hz in this calculation.

MODEL OF ADRC CONTROL

The cavity dynamics is represented by a parallel RLC circuit as shown in Figure 2. According to Kirchhoff's law, we have:

$$\frac{d^2\hat{V}_c}{dt^2}+\frac{\omega_0}{Q}\frac{d\hat{V}_c}{dt}+\omega_0^2\hat{V}_c=\frac{R\omega_0}{Q}\frac{d\hat{I}_c}{dt} \tag{1}$$

$$\hat{I}_c=\frac{(\hat{I}_g+\hat{I}_b)Z_{ext}}{Z_{ext}+Z_{cav}}\quad,\quad Z_{ext}=\frac{R}{\beta} \tag{2}$$

$$\hat{V}_c(t)=\vec{V}(t)e^{jw_g t}=V_c(t)e^{j\varphi_s(t)}e^{jw_g t} \tag{3}$$

$$\hat{I}_c(t)=\vec{I}_c(t)e^{jw_g t}=I_c(t)e^{j\theta(t)}e^{jw_g t} \tag{4}$$

Since $\dot{\vec{V}}_c << \omega_g\vec{V}_c$ and $\dot{\vec{I}}_c << \omega_g\vec{I}_c$, Eq. (1) can be simplified to first-order differential equation as:

$$\dot{\vec{V}}_c+\omega_{1/2}\left(\vec{V}_c-\frac{\hat{I}_b Z_{ext}}{Z_{ext}+Z_{cav}}R\right)+\frac{\Delta\omega}{j}\vec{V}_c=\omega_{1/2}\frac{\hat{I}_g Z_{ext}}{Z_{ext}+Z_{cav}}R \tag{5}$$

where ω_0 is cavity resonant frequency and Q is quality factor, β is coupling factor, $\tilde{I}_g$ is generated current, $\tilde{I}_b$ is beam induced current due to beam loading effect, $\tilde{I}_c$ is total current of cavity, $\tilde{V}_c$ is cavity voltage, ω_g is generator circular frequency, $\Delta\omega=\omega_0-\omega_g$ is the total cavity detuning by microphonics and tuner, $\omega_{1/2}=\omega_0/2Q$ is cavity half bandwidth, Z_{cav} and Z_{ext} is cavity and external impedance.

According to the model, we can define the output of cavity system as $y=\alpha\vec{V}_c$, cavity input as $u=I_g/A$. Eq. (5) can be simplified as $\dot{y}=f+bu$, where

$$f=-\alpha\omega_{1/2}\left(\vec{V}_c-\frac{\hat{I}_b Z_{ext}}{Z_{ext}+Z_{cav}}R\right)-\alpha\frac{\Delta\omega}{j}\vec{V} \tag{6}$$

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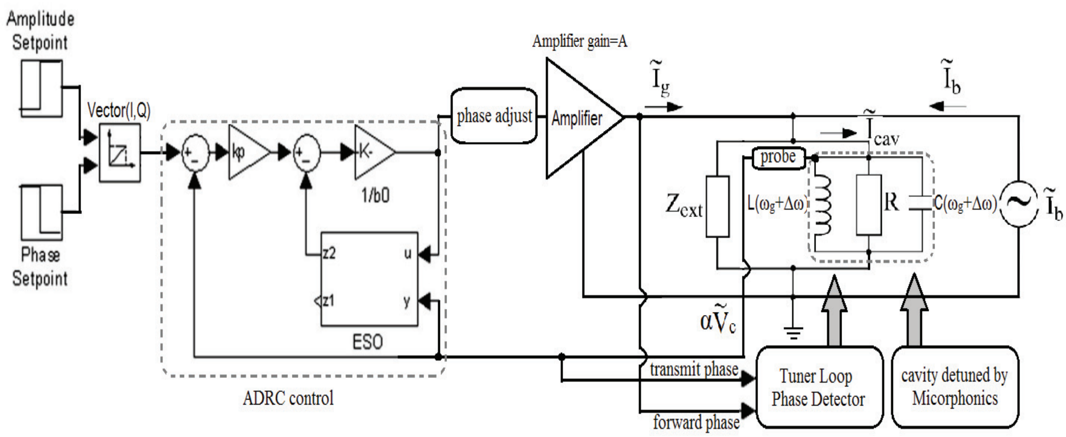

Figure 2: Model of ADRC control with new vector-control scheme

$$b = \alpha\omega_{1/2} AR \frac{Z_{ext}}{Z_{ext} + Z_{cav}} \qquad (7)$$

f is considered as the total disturbance, b is design parameter of cavity system. This conventional ADRC model [2] is simulated as shown in Section 3.

COMPARISON OF PI AND ADRC

We took an example of FRIB β=0.085 quarter-wave resonators (QWR085), which has a bandwidth of 40 Hz. Data sampling rate is set to be 25 kHz. For ADRC, the controller and observer bandwidths are set to 10000 and 20000 rad/s respectively. PI controller is tuned with a proportional gain of 600 and an integral gain of 2500. Those parameters were picked to achieve best stable response and far exceeded the limit of old scheme.

Compensation of Beam Loading

The average beam current for QWR085 cavity is 352 µA [3]. A bunch beam (2~2.5s) is assumed. Figure 3 and Figure 4 show the comparison of PI and ADRC control for amplitude and phase control. Both PI and ADRC can reject the beam loading effectively, with small amplitude fluctuation of ±0.08% and phase fluctuation of ±0.03°. PI takes much longer to get back to set point than ADRC.

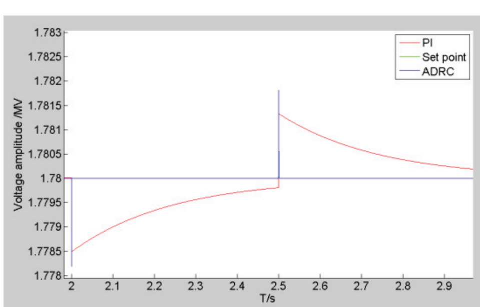

Figure 3: Cavity voltage amplitude fluctuation to reject beam loading. Amplitude's set point (1.78MV) is overlap with blue line.

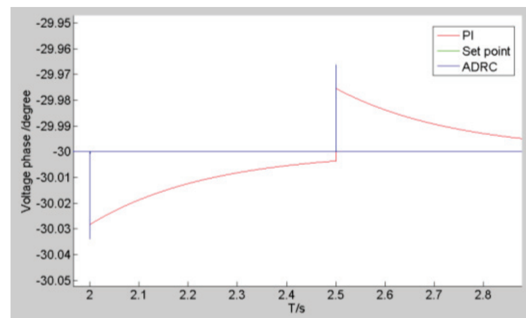

Figure 4: Cavity voltage phase fluctuation to reject beam loading. Phase set point (-30°) is overlap with blue line.

Microphonics

The frequency of microphonics is 60Hz and amplitude is set to be 20Hz, same as the maximum cavity detuning tolerance. Figure 5 and Figure 6 compare PI and ADRC to reject microphonics. The amplitude fluctuation is ±0.001% for PI and vanishing small for ADRC. Phase fluctuation is ±0.31° for PI and ±0.03° for ADRC. Obviously, ADRC performs better than PI in rejecting microphonics.

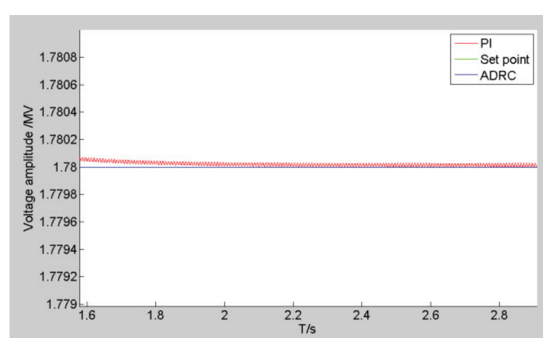

Figure 5: Cavity voltage amplitude fluctuation for microphonics. Amplitude's set point (1.78MV) is overlap with blue line.

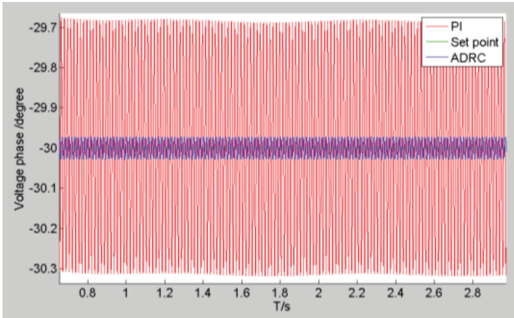

Figure 6: Cavity voltage phase fluctuation for microphonics. Green is set point=-30°.

PIEZO TUNER FOR MICROPHONICS

Piezo-tuner is driven by piezo actuators for fast and fine adjustments of cavity's frequency. Since piezo tuner is commonly used to compensate Lorenze Force Detuning (LFD) and microphonics for pulsed power accelerators, we also studied its feasibility to be included in PI and ADRC control systems.

In the simulation as shown in Figure 7, piezo tuner is assumed to be linear with a sampling rate of 25 kHz. Its tuning range is ±40 Hz without mechanical backlash.

Simulation shows that the response time of piezo tuner in ADRC should be smaller than 0.03 ms for stable response. Considering most piezo tuner response time is 0.1~1 ms, it is not the right choice for the current ADRC control. In PI control, the required piezo tuner response time should be less than 0.6 ms and it could be achievable. Figure 7 shows phase fluctuation reduced by a 0.5 ms piezo tuner. Figure 8 shows RF power used by ADRC for successful rejection without assistance from piezo tuner. Figure 9 shows RF power used by PI for successful rejection with help of piezo tuner.

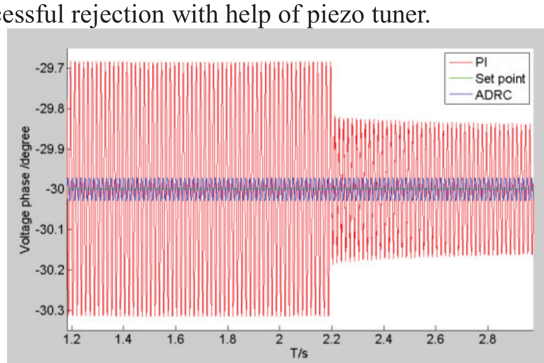

Figure 7: Phase fluctuation reduced by piezo-tuner. Piezo-tuner response time is set to 0.5 ms. Blue is ADRC without piezo-tuner, red is PI with a piezo-tuner turned on at 2.2 s.

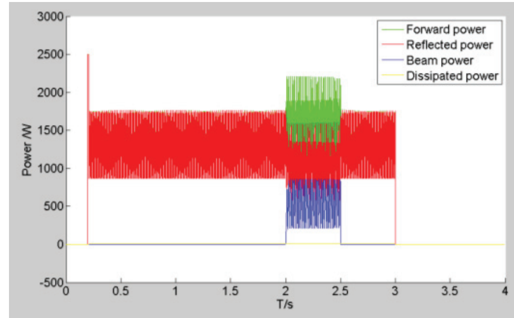

Figure 8: Power needed in ADRC without piezo-tuner. RF power is turned on at t=0.2s and off at t=3s. PI without piezo-tuner consumes similar RF power.

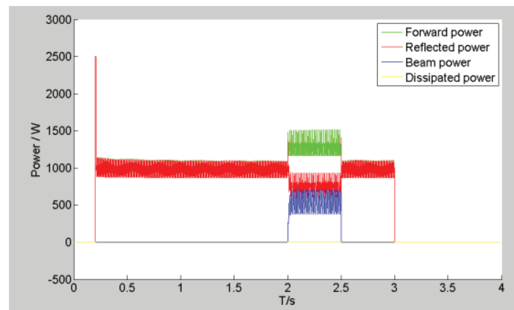

Figure 9: Power needed in PI with piezo-tuner. RF power is turned on at t=0.2s and off at t=3s.

Although piezo tuner can help save RF power by ~650W in PI control (compare with RF power by PI without piezo tuner), we still prefer a smaller phase fluctuation without piezo tuner with ADRC. Since FRIB cavity is operated at CW without Lorentz Froce Detuning (LFD), the RF power consumed to compensate microphonics without piezo tuner is still tolerable. In this sense, we prefer ADRC without piezo tuner to reject microphonics.

CONCLUSION

In this paper, we developed new control model with improved vector-control scheme to reject disturbances. ADRC and PI method have been studied respectively to compensate beam loading and microphonics. As ADRC reacts more quickly and fluctuates much less, we are inclined to use ADRC for FRIB LLRF system to reject beam loading and microphonics.

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