ADAPTIVE TUNER CONTROL IN TRIUMF ISAC 2 SUPERCONDUCTING LINAC USING KALMAN FILTER

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Abstract

The TRIUMF ISAC 2 RF control system uses phase locking self-excited control. Amplitude, phase and frequency control is achieved with I/Q voltage injection, and forward RF power is minimized with a tuner feedback loop. The phase difference between the input coupler and the output pickup drives a velocity servo system to provide tuning control. However, the presence of microphonics in the cryomodule, although under control by the quadrature loop, still presents significant interference to the phase error signal for the tuner. The tuner will follow this noise and generate more microphonics as a result. A first-order Kalman filter is used for an estimation of the phase difference and reduces the movement of the tuner.

INTRODUCTION

The ISAC 2 superconducting RF cavities have unloaded Q's of the order of 10^9. Even when operating under overcoupling condition the loaded Q's are still of the order of 10^7. At this high operating Q any slight detuning of the cavity will cause a large increase in power in order to keep the cavity at the operating voltage and frequency. This detuning arises from the fluctuation in helium pressure and microphonics. In-phase and quadrature-phase feedback is used to control the voltage and phase to a stable reference. The function of the tuner is to reduce the RF power requirement by keeping the detuning to within a prescribed limit. This frees all the reserve power to be used for phase locking in the presence of microphonics. To achieve this goal two tuning conditions are monitored: the phase difference between the input and output of the cavity, and the quadrature drive of the modulator required to maintain phase lock. However, both of these signals contain high frequency information whose sources are microphonics and power supply noise. The tuner controller, however, operates at a relatively low frequency of 10 samples/s and will not be capable of cancelling out the microphonics. Instead, a digital filter is used to remove the microphonics components, and Kalman filters are used to perform this task. We have chosen a <u>S</u>ingle <u>I</u>nput <u>S</u>ingle <u>O</u>utput Kalman filter as a test of principle.

RESONATOR TUNING CONTROL

The TRIUMF ISAC 2 superconducting RF cavities operate under phase-locked self-excited operation[1]. The basic phase-locked self-excited loop is shown in Fig. 1. V_i and V_q are the in-phase and quadrature phase components of the drive signal, respectively. Let θ_l be the phase delay around the main loop, θ_f be the additional phase delay around the quadrature correction branch and ω_c be the resonant frequency of the cavity. The system will oscillate at a frequency $\omega_{se} = \alpha/t$ and the voltage at the cavity V_o is [2]

$$V_0\left[1 + i\,\tau(\omega_{se} - \omega_c)\right] \approx \gamma\left(e^{i\theta_l}V_i + ie^{i\theta_q}V_q\right) \quad (1)$$

where τ is the loaded time constant of the cavity and γ is the voltage multiplication ratio.

The argument part of Equation 1 gives

$$\tau(\omega_{se} - \omega_c) = \frac{V_i \sin\theta_l - V_q \cos\theta_q}{V_i \cos\theta_l + V_q \sin\theta_q} \quad (2)$$

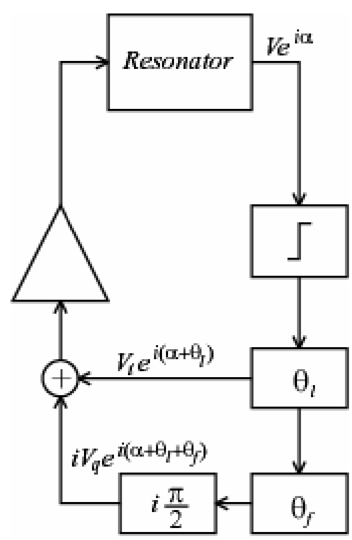

Figure 1: Self-excited system with phase locking.

From Equation 2, for small values of θ_l and θ_f, we have

$$\frac{V_q}{V_i} \approx \theta_l - \tau(\omega_{se} - \omega_c) \quad (3)$$

The total power required from the amplifier is

$$P \propto V_i^2 + V_q^2 \quad (4)$$

Since ω_c is affected by microphonics and detuning, and V_q is used to vary the phase shift around the loop to phase lock ω_c to ω_r, while the tuning motor is used adjust the average value of ω_c and thus V_q in order to minimize RF power.

The tuner has been described in a previous paper[3]. It is a mechanical device driven by a linear servo motor. The control circuit of this servo motor is proprietary. Incorporated with the servo motor system are feedback loops for position feedback. Rate feedback is simulated by incrementing an internal position setpoint counter. The tuner was originally designed to be able to compensate for microphonics, however the control circuit is only able to accept digital commands at an maximum rate of 20 commands per second, resulting in a rather small control bandwidth.

The control of the tuning motor can be derived from two sources, first from the average value of V_q, and second from the phase difference ϕ between the input and the output of the cavity.

$$\phi = \tan^{-1}\tau(\omega_r - \omega_c)$$

Both of these signals are theoretically equivalent. Practically however, there are difference between them, mainly due to misalignment in the loop for the first case and misalignment in the phase detector for the second case. Also both of these signals have microphonics signatures at frequencies higher than the response of the mechanical tuner. If we use these raw signals to drive the tuning motor, the result would be noisy operation of the motor and we may even introduce more microphonics into the system.

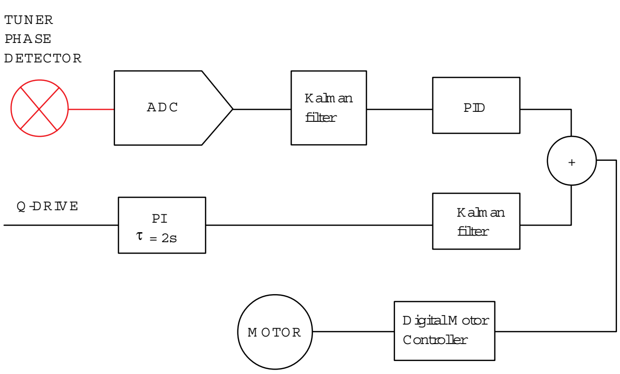

Figure 2: Placement of Kalman filters in tuner control loop.

A simple low pass filter can remove the microphonics component of the detuning signal, this however is a brute force method. But when the system state is well known an optimal filter such as a Kalman filter can provide much better performance.

KALMAN FILTER

A Kalman filter [4] estimates the system state by reproducing the system architecture, and refines the estimation at every time step by comparing the previous estimates with the present measurement.

Implementation

For a discrete system, let x_j be the system state at time step *j*. The discrete state equation is:

$$x_j = Ax_{j-1} + Bu_j + w_j \tag{5}$$

where *A* is the transition matrix and w_j is the system noise with covariance *Q*

$$Q \equiv E\{w_j^2\} \tag{6}$$

The observable z_j depends on the system state x_j,

$$z_j = hx_j + v_j \tag{7}$$

with v_j being the measurement noise with covariance *R*

$$R \equiv E\{v_j^2\} \tag{8}$$

For a Single Input Single Output (scalar) system, we have $A = 1, B = 0$ and $h = 1$.
Therefore

$$x_j = Ax_{j-1} + w_j \tag{9}$$

and

$$z_j = x_j + v_j \tag{10}$$

The process has two steps, a predictor step (which calculates the next estimate of the state based only on past measurements of the output), and a corrector step (which uses the current value of the estimate to refine the result given by the predictor step).

Predictor

The Predictor projects the current state estimate ahead in time. The a priori state estimate $\hat{x}_j^-$ is based on the previous estimate of the state $\hat{x}_{j-1}$ and the current value of the input $u_j = 0$. For our SISO system, the predictor step gives

$$\hat{x}_j^- = \hat{x}_{j-1} \tag{11}$$

The a priori covariance p_j^- is given by

$$p_j^- = p_{j-1} + Q \tag{12}$$

Corrector

The Corrector adjusts the projected estimate by an actual measurement at that time. To correct the a priori estimate, we need the Kalman filter gain, k_j, given by

$$k_j = \frac{p_j^-}{p_j^- + R} \tag{13}$$

This gain is used to refine the a priori estimate to give us the a posteriori estimates.

$$\hat{x}_j = \hat{x}_j^- + k_j(z_j - \hat{x}_j^-) \tag{14}$$

and we can now calculate the a posteriori covariance from the a priori covariance

$$p_j = p_j^-(1-k_j) \tag{15}$$

Kalman Cycle

The Kalman cycle recursively performs the predictor step and the corrector step at every time step. Due to the simplicity of the model the predictor and corrector step can be combined together. By combining Eq.7 and Eq. 10 one gets

$$\hat{x}_j = \hat{x}_j + k_j(z_j - \hat{x}_j) \tag{16}$$

and combining Eq.8 and Eq.11 one gets

$$p_j^- = p_{j-1}^-(1-k_{j-1}) + Q \tag{17}$$

Eq.12 is the familiar Infinite Impulse Response single pole low pass filter, with k_j as the filter coefficient. The Kalman filter differs from an ordinary low pass filter because of the dependence of k_j on the covariances *R* and *Q*. To make the filter adaptive, the covariances are estimated using the running measured value. The measurement noise covariance *R* is

$$R \approx E\{(z_j - \hat{x}_j)^2\} \approx E\{(x_j - \hat{x}_j)^2\} \tag{18}$$

The process noise covariance *Q* is more difficult to estimate. If we assume that this is due to digitizing noise alone, then

$$Q \approx 0.25$$

RESULTS

As mentioned in the above section, the tuner drive signal is derived from the phase difference between the input and the output of the cavity and as well the average of the quadrature drive voltage. Figure 3 shows the result of the drive signal of the tuner when the filter is switched

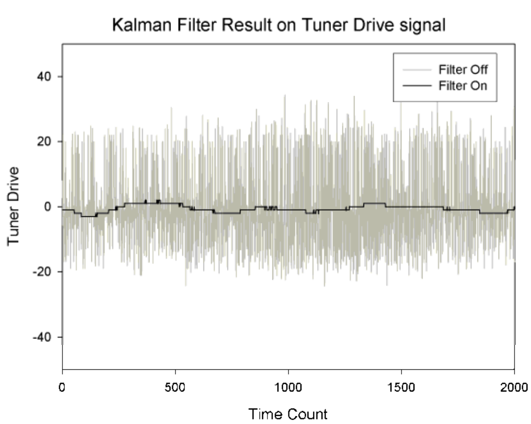

Figure 3: Tuner drive signal with/without filter.

off and switched on. With the filter switched off, the drive signal contained a lot of fluctuations in either direction. The high frequency components of this fluctuation are attenuated by the tuner response and the tuner position is shown in Fig.4. The tuner position still showed the presence of microphonics in the form of oscillations in its position.

With the filter switched on, the drive signal consists only of the slow fluctuation due to helium pressure variation. Since the control bandwidth of the tuner is much smaller then the control bandwidth of the phase regulating loop, the use of Kalman filter on the tuning loop does not either improve or adversely affect the phase noise of the RF. But since the movement of the tuner is reduced, the instantaneous drive requirement is reduced.

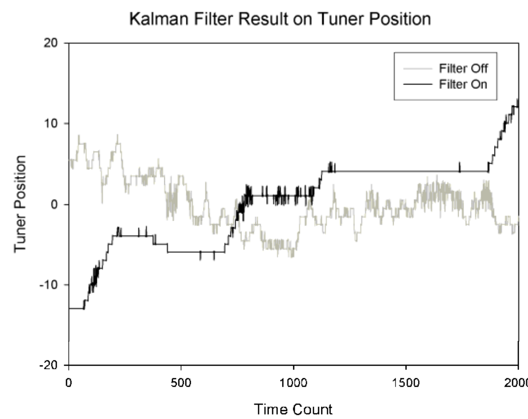

Figure 4: Tuner position with/without filter.

FUTURE WORK

We have tried using two very simple SISO Kalman filter as a test of principle. There are actually multiple factors affecting the position of the tuner, and Multiple Input Single Output state is a more suitable description for the control of the tuner.

REFERENCES

[1] K. Fong, M. Laverty and S. Fang, "Status of RF Control System for ISAC II Superconducting Cavities", Proc. Linac 04, p. 450.

[2] J.R. Delayen, "Phase and Amplitude Stabilization of Beam-Load Superconducting Resonator", Proc. Linac 92, p. 371.

[3] T. Ries, K. Fong, S. Koscielniak, R.E. Laxdal, G. Stanford, "A Mechanical Tuner for the ISAC-II Quarter Wave Superconducting Cavities", Proc. 2003 Part. Acc. Conf, p. 1488.

[4] R.E. Kalman, "A New Approach to Linear Filtering and Prediction Problems", Trans. ASME-J. Basic Engineering, p. 35 (March 1960).