TUNER CONTROL IN TRIUMF ISAC 2 SUPERCONDUCTING RF SYSTEM

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Abstract

The TRIUMF ISAC 2 superconducting RF system operates in self-excited, phase locking mode. A mechanical tuner is used to minimize the required RF power. The tuner derives the tuning information from the phase shift around the self-excited loop. Its accuracy is however reduced by phase drift in amplifiers and cables due to thermal effects. The cross product between the amplitude and the phase errors is used to detect this drift. The signal derived from the cross product does not depend on any initial value adjustment. Furthermore, no special adjustment is required and the measurement can be performed online during beam production.

INTRODUCTION

A simplified block diagram of a self-excited, phase locking oscillator is shown in Fig. 1. Self-excitation is self sustaining when the loop gain is larger than unity and the self-excited frequency ω will be such that the phase lag around a complete loop is an integer multiple of 2π. This overall phase lag is the sum of the phase shift ϕ of the RF cavity, the phase modulation δ from the control system, and the phase lag θ for the rest of the system. Not shown in the figure are amplitude and phase detectors located at the output of the resonator. The outputs of these detectors are used for feedback regulation. IQ modulation is used for ISAC 2 where the amplitude is controlled by V_i and the frequency/phase is regulated by V_q.[1,2] Optimal system performance is obtained when the self-excited frequency is equal to the resonance frequency ω_r of the cavity. This can be achieved by the adjustment of θ. ω_r can then be adjusted to match an external reference frequency by adjustment of the tuner. However, long-term drifts, due to thermal effects on the amplifier and cables, will cause these phase values to deviate from the initial optimal values. The problem is how to measure these deviations and restore the phases back to optimum. Typical measurement of phase always requires two additional cables to the phase measuring device, introducing additional offsets into the result. As will be shown in the next section, the signal derived from the cross product does not require any extra equipment and does not have any offset.

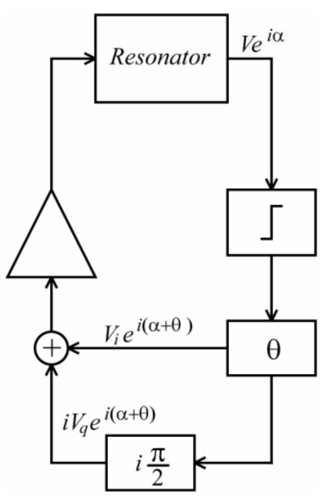

Figure 1: Block diagram of Self-excited System.

THEORY

Phase Relationship in a Self-excited Loop

The phase relation in a self-excited loop obeys

$$\theta + \delta + \phi = 2n\pi\ . \tag{1}$$

The phase shift ϕ of the RF cavity is given by

$$\phi = \tan^{-1}(\omega_r - \omega)\tau\ . \tag{2}$$

Also the I/Q modulator produces a phase shift δ given by

$$\delta = \tan^{-1}\frac{V_q}{V_i} \tag{3}$$

Therefore

$$\theta + \tan^{-1}\frac{V_q}{V_i} + \tan^{-1}(\omega_r - \omega)\tau = 2n\pi$$

To optimize system performance and to minimize RF power requirement, the self-excited system should be tuned such that

$\delta = \phi = 0$ and $\theta = 2n\pi$

Since V_i and V_q can be measured directly, it required that θ be known in order to optimize the system.

System Equation for Feedback Regulators

The equations for the self-excited system are [3,4] :

$$\begin{bmatrix}\delta V \\ \delta\omega\end{bmatrix} = \begin{bmatrix} G_{aa} & G_{ta} \\ G_{a\omega} & G_{t\omega}\end{bmatrix}\begin{bmatrix}\delta v_i \\ \delta v_q\end{bmatrix} \tag{4}$$

where

$$G_{aa} = \frac{\gamma\cos\theta}{1+\tau s},$$

$$G_{ta} = -\frac{\gamma\sin\theta}{1+\tau s},$$

$$G_{a\omega} = \frac{\gamma\cos\theta}{V_0\tau}\left[\tan\theta + \frac{\tan\phi}{(1+\tau s)}\right],$$

and

$$G_{t\omega} = \frac{\gamma\cos\theta}{V_0\tau}\left[1 - \frac{\tan\theta\tan\phi}{(1+\tau s)}\right].$$

If either $\theta \neq 0$ or $\phi \neq 0$, the result is cross coupling between the amplitude and phase. When feedbacks are being applied, this cross coupling will cause system performance to degrade. First system stability is decreased due to the cross coupling. Second microphonics now affects not only the cavity phase, but the cavity

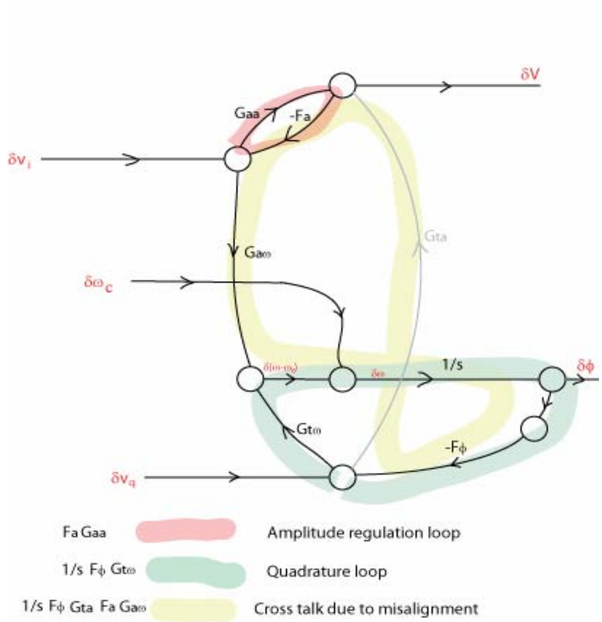

Figure 2: Signal flow chart of Amplitude and Phase regulated self-excited system.

amplitude as well, increasing system noise.

Using the signal flow chart in Figure 2, where F_a, F_ϕ are the amplitude and phase feedback gains, respectively, and using Mason's rule we can get the closed loop phase response due to resonator frequency change:

$$\delta\phi = \frac{\delta\omega}{sD}\left(1 + F_a G_{aa}\right) \tag{5}$$

and amplitude response due to resonator frequency change:

$$\delta v = \frac{\delta\omega}{sD}\left(-F_\phi G_{ta}\right) \tag{6}$$

with

$$sD = s\left(1 + \frac{F_a \gamma \cos\theta}{1+\tau s}\right) + \frac{F_\phi \gamma \cos\theta}{V_0 \tau}\left[1 - \frac{\tan\theta \tan\phi}{(1+\tau s)}\right] + \frac{F_a F_\phi \gamma^2}{1+\tau s}\frac{1}{V_0 \tau}$$

Without loss of generality we can assume proportional feedback and let

$$\gamma F_a \cos\theta = \tau K_a - 1,$$

$$\gamma F_\phi \frac{1}{V_0 \tau}\cos\theta = \gamma \Im_\phi \mathrm{K}_\phi \frac{1}{V_0 \tau}\cos\theta = K_\phi,$$

where $\Im_\phi$ is the phase feedback proportional gain, K_ϕ is the phase detector conversion gain. K_a and K_ϕ have dimensions of s^{-1} are the normalized loop gains of the amplitude and phase loops, respectively. Thus

$$sD = \frac{\tau}{1+\tau s}\left[s^2 + 2\zeta\chi s + \chi^2\right]$$

where

$$2\xi\chi = K_a + K_\phi$$

and

$$\chi^2 = K_\phi\left(K_a \sec^2\theta - \frac{1}{\tau}\tan\theta\left(\tan\theta + \tan\phi\right)\right)$$

Error Products

The phase error (Equation 5) then becomes

$$\delta\phi = \delta\omega \frac{\left(s + K_a\right)}{s^2 + 2s\zeta\chi + \chi^2} \tag{7a}$$

Its inverse Laplace transform give the phase response in time domain for an impulse $\delta\varphi$:

$$\delta\phi = \delta\varphi e^{-\xi\chi t}\left\{\cos\Omega t + \left(K_a - \zeta\chi\right)\frac{1}{\Omega}\sin\Omega t\right\} \tag{7b}$$

where $\Omega = \chi\sqrt{1-\zeta^2}$

The amplitude error (Equation 6) becomes:

$$\delta v = \delta\omega \frac{V_o K_\phi \tan\theta}{s^2 + 2s\zeta\chi + \chi^2} \tag{8a}$$

and in time domain,

$$\delta v = \delta\varphi e^{-\zeta\chi t} V_o K_\phi \tan\theta \frac{1}{\Omega}\sin\Omega t \tag{8b}$$

The time averages of Equation 7 or 8 are zero and do not yield information on misalignment. The cross product of the phase error and the amplitude error is

$$\delta\phi\delta v = \delta\varphi^2 e^{-2\zeta\chi t} V_o K_\phi \tan\theta \cdot$$

$$\frac{1}{\Omega}\sin\Omega t\left\{\cos\Omega t + \left(K_a - \zeta\chi\right)\frac{1}{\Omega}\sin\Omega t\right\}$$

and the time average is

$$\overline{\delta\phi \cdot \delta v} = \overline{\delta\varphi^2} V_o K_\phi K_a \tan\theta \frac{1}{4\zeta\chi^3} \tag{9}$$

Meanwhile

$$\overline{\delta\phi^2} = \overline{\delta\varphi^2}\frac{1}{4\zeta\chi^3}\left[\zeta^2 + K_a{}^2\right] \tag{10}$$

The normalized form of the cross product does not give an indication of how far the system is away from the required tuned. The semi-normalized form is

$$\frac{\overline{\delta\phi \cdot \delta v}}{\overline{\delta\phi^2}} = \frac{V_o K_\phi K_a}{\left[\zeta^2 + K_a^2\right]}\tan\theta \tag{11}$$

Since the damping $\zeta \approx 1$ and $K_a >> 1$, Equation 11 reduces to

$$\frac{\overline{\delta\phi \cdot \delta v}}{\overline{\delta\phi^2}} \cong \mathrm{K}_\phi \frac{\Im_\phi}{F_a} \tan\theta \qquad (12)$$

Equation 12 states that the semi-normalized cross product of the errors is a monotonic function of θ, and independent on ϕ. Furthermore, its magnitude depends only θ and the feedback gains. Thus the semi-normalized cross product of the amplitude error and the phase error gives the direction of mistuning in the phase of the transmission line.

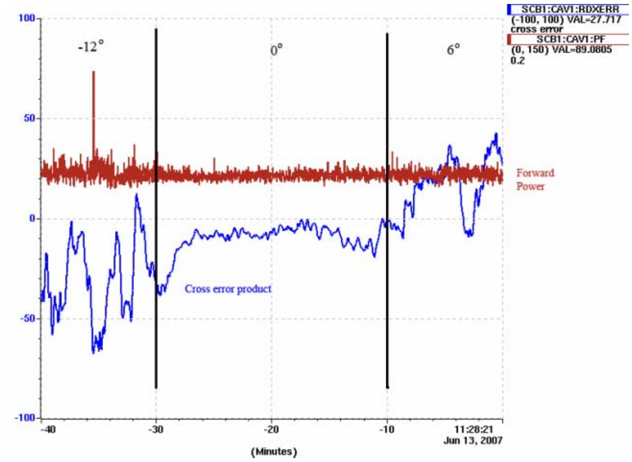

Figure 3: Strip charts of θ and forward power with ϕ kept constant.

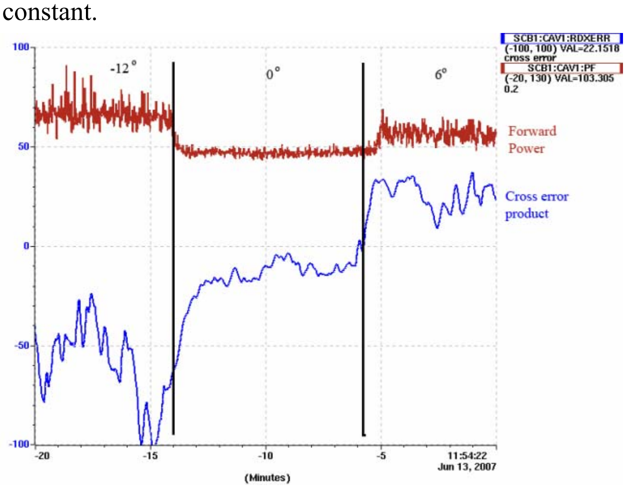

Figure 4: Strip charts of θ and forward power with δ kept constant.

MEASUREMENTS

To obtain a true presentation of the cross product term, the amplitude and phase error must be sampled at the "same" time, i.e. the time difference between the sampling of the amplitude and the phase should be only a small fraction of the shortest period of the microphonics. In the ISAC-2 RF control system a single DSP performs both the amplitude and phase regulations. The amplitude and phase errors are sampled within 10 μs of each other by the DSP. These values are read by the supervisory computer; the cross error product is calculated and made available to EPICS. Time averaging is performed using a first order IIR filter with filter coefficient of 0.001. To see the dependence of cross error product on θ, the cross error product can be plotted on a strip chart, with θ stepped through a small range by manually adjusting a manual phase shifter. Figure 3 shows the results with ϕ being held constant at zero, θ is changed and δ is allowed to compensate for the change. The line phase is increased in steps as time progress, the cross-product (in blue) and the forward power (in brown) is plotted. When $\theta \neq 0$, the cross product also deviates from zero, its fluctuation as well the fluctuation of the forward power are also increased. As the cross error product approaches zero, its fluctuation, as well as the fluctuation of the forward power, are reduced. In this figure the tuner did not move, the average forward power remains constant despite changes in θ and δ as expected. Figure 4 shows another case that while varying θ, δ are held constant at 0 instead while ϕ are allowed to change. The cross product behaves similarly in both cases, indicating that the cross product depends only on θ. In this figure the forward power does change with different values of cross error product, with minimum when the cross error product is zero. This is also expected because the resonator has to operate off-resonance to cancel the change in θ.

CONCLUSION

Unwanted phase shift in a self-excited loop can be detected online by the cross product of the amplitude and phase errors. This provided a reliable way for retuning of the system for minimum RF power requirement as well as optimum system performance. Although the calculations and the measurements were done using amplitude and phase detectors, in principle the results should be similar for I/Q detectors.

REFERENCES

[1] K. Fong, M. Laverty, S. Fang, "RF Control System for ISAC II Superconducting Cavity Test Stand", Proceedings of the LINAC 2002, Gyeongju, Korea, August 2002.

[2] K. Fong, S. Fang, M. Laverty, "RF Control System for ISAC II Superconducting Cavities", Proceedings of the 2003 Particle Accelerator Conference, Portland, USA, May 2003.

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

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

