SELF-TUNING REGULATOR FOR ISAC 2 SUPERCONDUCTING RF CAVITY TUNER CONTROL

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Abstract

The ISAC 2 superconducting RF cavities use the self-excited, phase-locked mode of operation. As such the microphonics are sensitive to the alignment of the phase control loop. Although initial alignment can minimize the effect of microphonics, amplitude-dependent phase shift and long term drift, particularly in the power amplifiers, can cause the control loop misalignment and an increase in sensitivity to microphonics. The ISAC 2 control system monitors several points in the control loop to determine the phase alignment of the power amplifiers as well as the RF resonant cavities. Online adaptive feedback using Self-Tuning Regulator is employed to bring the different components back into alignment.

INTRODUCTION

Figure 1 shows the block diagram of a self-excited system. In this type of system amplitude control is achieved by feedback regulation of the In-phase channel, while frequency and phase control are achieved by feedback regulation of the Quadrature-phase channel.

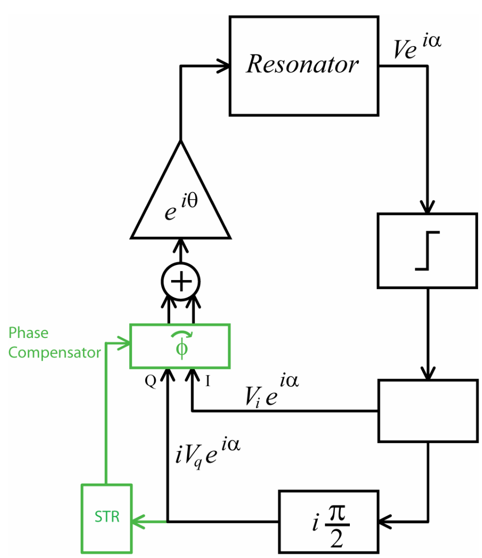

Figure 1: Phase-locked Self-excited loop with Self-Tuning phase compensator.

The feedback signal is derived by comparing the phase of the self-excited signal with an external reference frequency. In ISAC 2, the I/Q feedback controller functions are performed by a single digital signal processor[1], while the phase comparison is done by a FPGA[2]. Proper phase-locked operation and the amount of residual microphonics in the feedback system depends on its alignment[3]. This includes the phase delays of the cables, the amplifier system as well as the resonant cavity. Phase delay changes in all these components can be caused by cryogenic helium pressure, thermal effects and long term deterioration such as power tube emissivity. To counter act these changes a digital phase shifter, coloured in green in Figure 1, is incorporated into the feedback controller DSP. This phase shifter is essentially a rotation matrix operating on the In-phase and the Quadrature-phase channel outputs of the DSP. The phase sifter is controlled by a self-tuning regulator for automatic phase noise reduction. The self-tuning regulator monitors the original Q channel output, then calculates the optimum drive to modify the rotation angle.

THEORY

The equation for the voltage of the cavity is [1]

$$\ddot{v} + 2\frac{1}{\tau}\dot{v} + \omega_c^2 v = 2\frac{\gamma}{\tau}\dot{V}_g \qquad (1)$$

Using the I and Q components of the input voltage V_g as the independent variables and the amplitude and phase of the output voltage v as the dependent variables for a phase-locked self-excited system, the equation of state is

$$\begin{bmatrix}\delta V\\ \delta\omega\end{bmatrix} = \gamma\cos\theta \begin{bmatrix} \frac{1}{s\tau+1} & -\frac{\tan\theta}{s\tau+1} \\ \frac{1}{\tau V_0}\left(\tan\theta - \frac{\tan\phi}{s\tau+1}\right) & \frac{1}{\tau V_0}\left(1 - \frac{\tan\phi\tan\theta}{s\tau+1}\right)\end{bmatrix}\begin{bmatrix}\delta v_i\\ \delta v_q\end{bmatrix} \qquad (2)$$

The phase shift ϕ of the RF cavity is given by

$$\phi = \tan^{-1}(\omega_c - \omega)\tau \qquad (3)$$

and the I/Q modulator produces a phase shift ρ given by

$$\rho = \tan^{-1}\frac{V_q}{V_i} \qquad (4)$$

The phase relation in a self-excited loop must obey

$$\theta + \rho + \phi = 2n\pi \qquad (5)$$

In order to minimize the power requirement, ϕ should be set to zero. While ϕ can be measured directly from the phase difference between the input and the output of the cavity, θ is a dynamic variable, namely the amplifier phase shift. In self-excited mode θ and ϕ are not independent variables since they must obey Equation 5. Therefore when ϕ is set to zero by the tuner, and when $\theta = 0$, $q \equiv V_q = 0$. This is operationally desirable since it eliminates cross-talk between the I and the Q channels. Another important reason for $\theta = 0$ is that when this condition is not met, the cross-talk between the I and Q channel outputs can in some cases trip the built-in limiters in the PID controllers and causes both the amplitude and the phase loops to lose regulation.

Although q can be measured quite easily, it is contaminated with noise due to microphonics in the cavity. In addition, the relationship between q and θ is variable depending on the misalignment and the drive level. Therefore for these reasons a self-tuning regulator (STR) with recursive least square estimator is used to control θ.

IMPLEMENTATION

Phase Rotator

In ISAC 2 RF systems, a single DSP performs both the I and Q channel feedback control. Output limiting on the I and Q channels is implemented to prevent integrator wind-up. The DSP then accepts 4 parameters from the supervisory PC and performs the matrix multiplication on the I and Q outputs

$$\begin{pmatrix} I_1 \\ Q_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} I_0 \\ Q_0 \end{pmatrix} \tag{6}$$

With an input parameter of θ, the supervisory PC supplies these 4 parameters as

$$A = D = \cos\theta \tag{7a}$$

and

$$C = -B = \sin\theta \tag{7b}$$

The rotated digital outputs are converted into analogue signals for the complex modulator. There are 2 ADC's that monitors the I and Q inputs to the complex modulator. Since the phase rotator has already been applied with the DSP, the supervisory PC reads these 2 ADC's and apply the inverse of the rotation matrix to get the original I and Q output.

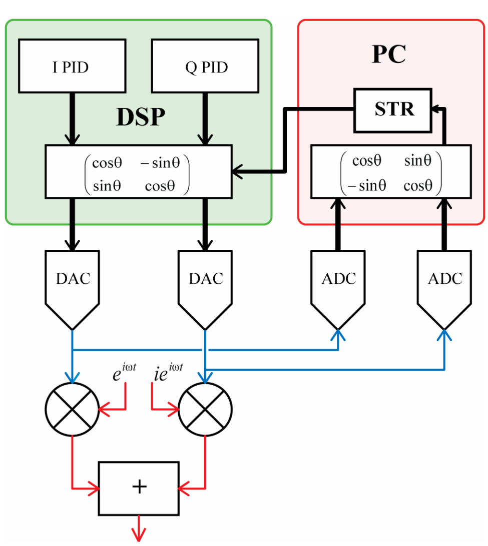

Figure 2: Implementation of phase rotator.

Self Tuning Regulator

Since the sampling frequency of the STR is much lower than the frequencies of the harmonics, q will be filtered to prevent aliasing before it is used as the input to the STR. Therefore the STR as shown in Figure 3 is assumed to have a first order system equation:

$$q(t) = b_0 + b_1\theta(t) + n(t) \tag{8}$$

where $n(t)$ is a zero mean Gaussian noise, b_0 and b_1 are the process parameters. b_0 is the misalignment and b_1 depends on V_o. Their estimates $\hat{b}_0$, $\hat{b}_1$ are obtained from a Recursive Least Square Estimator. Defining

$$\Phi^T(t) = [1 \quad \theta(t)] \tag{9a}$$

and

$$\Theta^T(t) = [b_0 \quad b_1] \tag{9b}$$

As we are trying to minimize $q(t)$, the residue is simply

$$\varepsilon(t) = q(t) \tag{10}$$

The Recursive least-squares estimation $\hat{\Phi}(t), \Theta^T(t)$ then satisifies the recursive equations [4]

$$\Theta^T(t) = \Theta^T(t-1) + K(t)q(t) \tag{11a}$$

With exponential forgetting factor λ to account for slow varying drifts,

$$K(t) = P(t-1)\Phi(t)\left(\lambda + \Phi^T(t)P(t-1)\Phi(t)\right)^{-1} \tag{11b}$$

$$P(t) = \left(I - K(t)\Phi^T(t)\right)P(t-1)/\lambda \tag{11c}$$

with the initial conditions on the covariance p_matrix

$$P(0) = \left(\Phi^T(0)\Phi(0)\right)^{-1} \tag{12a}$$

and estimated process-parameter vector

$$\Theta^T(0) = P(0)\Phi^T(0)q(0) \tag{12b}$$

The STR then has the following control law,

$$\theta(t) = \frac{q(t) - \hat{b}_0}{\hat{b}_1} \tag{13}$$

where the static misalignment is accounted for by $\hat{b}_0$, which has been internally integrated by the Kalman filter[5] within the Recursive Least Square Estimator.

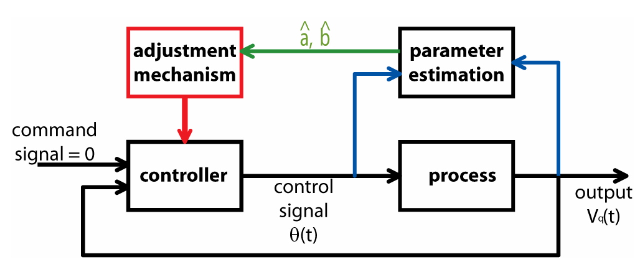

Figure 3: Block diagram of a self-tuning regulator.

The bulk of the self-tuning regulator is implemented in the supervisory PC for three reasons: First- the misalignment drift is a very slow process, and a fast sampling rate is not necessary, second- the DSP employed in ISAC 2 control is a fixed-point DSP, whereas the supervisory PC can perform 64-bit floating-point operations, and in addition has practically unlimited memory resources. The third reason is that the PC is programmed in C++ while the DSP is programmed in Assembler (optimized for speed).

RESULT

The phase rotators were implemented in all ISAC 2 RF control systems in 2007, and a self-tuning regulator is being tested on the test cryostat in the ISAC 2 test facility. Figure 4 shows the phase noise of the RF field voltage at various degrees of misalignment. The peaks at 58 Hz are due to external excitations such as pumps and fans. As can be seen in the figure, phase noise increases for progressively with misalignment in one direction, while it has little effects in the opposite direction.

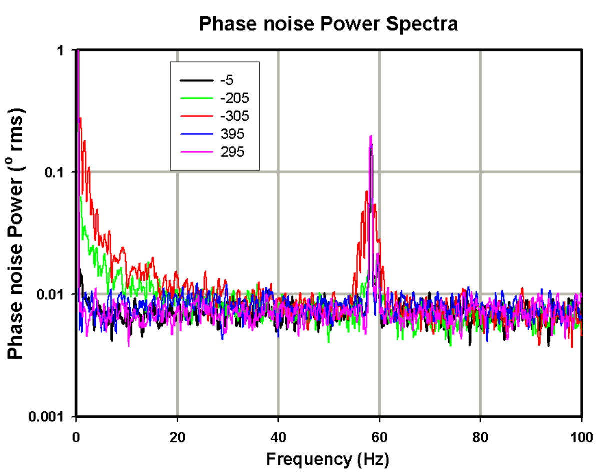

Figure 4: Phase noise of ISAC 2 cavity at different degrees of misalignment.

Figure 5 show a computer simulation of the self tuning regulator in action. A series of curves were superimposed on each other to represent the same initial misalignment but with different random noises of the same level. These noises are zero-mean Gaussian noise with a standard deviation of 50 units. The red curves represent the Q drives, corrupted by the noise, required to compensate a misalignment. For all cases, within 20 time steps the Q drives have been reduced from a high value of 1000 to close to 0, where the required phase shift to compensate the misalignment is taken over by the phase rotator (blue curves). After the regulator has converged, there are still some control movements due to the random noise. This noise actually prevents the covariance *p*_matrix from winding-up. In an actual implementation there should be a dead-band on the control to prevent unnecessary control inputs. This dead-band control would simply stop the updating of the self-tuning regulator but continue to monitor *q*. As soon as *q* exceeded a pre-determined threshold the covariance *p*_matrix would reset and the self-tuning regulator re-activated.

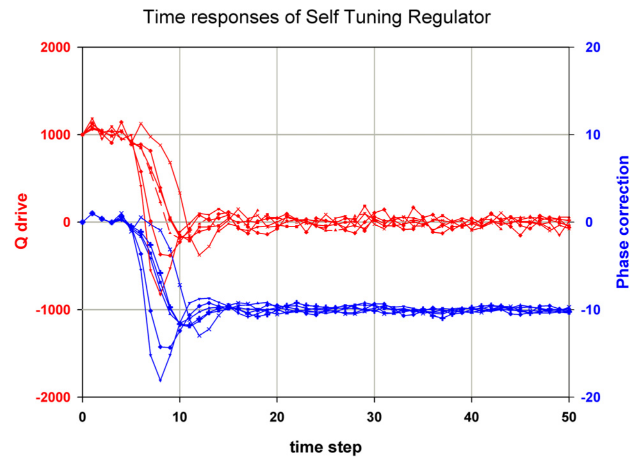

Figure 5: Simulation of Self Tuning Regulator for misalignment compensation.

CONCLUSION

Accurate alignment is very important to the performance of the ISAC 2 superconducting cavities, particularly to the suppression of phase noise. Long term phase drift in the system can adversely affect this alignment. A self-tuning regulator can be implemented with no hardware change to compensate for this slow varying drift in alignment. The regulator can provide optimum control in the presence of phase noise and with varying system parameters. The recursive least-square estimator is the heart of the regulator. Using the proper least-square error function, the regulator is able to track change in system parameters online and automatically bring the system back to the optimum alignment.

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