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TUNERS ALIGNMENT ON TWO 9-CELL CAVITIES WITH SINGLE AMPLIFIER UNDER SELF-EXCITED LOOP

Ken Fong, Zhengting Ang, Michael Laverty, Qiwen Zheng, TRIUMF, Vancouver, Canada

Abstract

The TRIUMF eLinac ACM consists of two 9-cell cavities which are driven by a single klystron. The output power from the klystron are split by a variable power divider and send down 2 independently phase adjustable transmission lines to their respective cryomodules. The vector sum of the fields from both cryomodules is used for phase-locked self-excited loop regulation. An automatic procedure to tune the 2 cyromodules to provide the correct amplitudes and phases for self-excitation as well as beam acceleration is described.

INTRODUCTION

In TRIUMF, ISAC-2 superconducting RF cavities are operating in the self-excited mode and tuned using the Minimum Quadrature Algorithm1, where a tuner is moved to seek the minimum quadrature drive. However, in the eLinac it is not possible to do so because we have only one quadrature drive but two independent tuners. So the phase comparison method is used to move each tuner. But due to the high operating frequency of 1.3GHz and the long cable run from the cavity to the phase detectors, the long term calibration of the phase detector is poor due to diurnal temperature variation. It is desirable to have a semi-automatic recalibration procedure to tune the 2 cryomodules while beam production is underway. This is performed by using a modified Minimum Quadrature Algorithm on the two cavities, then setting the phase reference settings according to the now newly tuned set-points for the two cavities.

THEORY

We start with the basic equation for a resonance cavity as shown in Fig. 1:

$$\frac{\ddot{V}}{2} + i\omega\dot{V} + \frac{i\dot{\omega}V}{2} + \frac{1}{\tau}\left(\dot{V} + i\omega V\right) + \omega(\omega_c - \omega)V = i\frac{\beta}{\tau(1+\beta)}\left(\omega v_g + \dot{v}_g\right) \qquad (1)$$

where V is the output voltage of the cavity and v_g is the input. ω is the excitation frequency and ω_c is the cavity resonant frequency. Defining $\gamma = \frac{\beta}{1+\beta}$ and in steady state, the time derivatives are zero. Eq.1 reduces to

$$V - i\tau(\omega - \omega_c)V = \gamma v_g \qquad (2)$$

Define the detuning angle ϕ where $\tan\phi = \tau(\omega - \omega_c)$

$$V = \gamma\cos\phi e^{i\phi} v_g \qquad (3)$$

This relationship is plotted in Fig. 2 with the imaginary part $\Im(v_g) = 0$ (self-excited) and $V_{q=0}$ (self-excited phase locked). As can be seen in the figure and from Eq. (3), the minimum drive power required is when $\phi = 0$. However, this obvious procedure is not easily to perform in a large machine because of the difficulty in obtaining an absolute measurement of ϕ. We therefore will use the quadrature input voltage, which can be obtained easily, to achieve the tuning result desired.

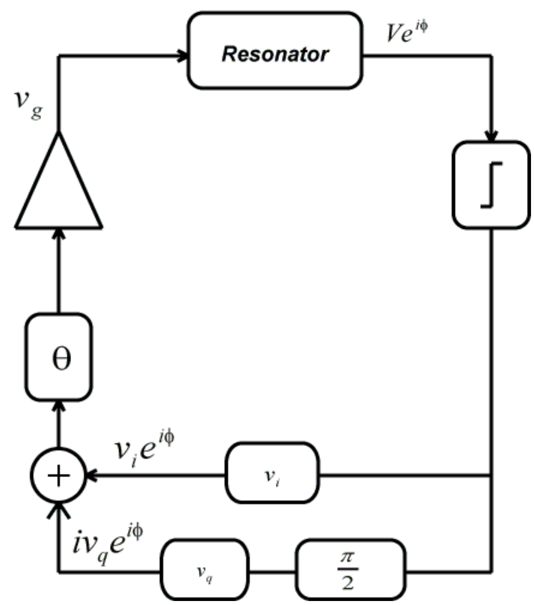

Figure 1: Self excited phase-locked loop.

SINGLE CAVITY SELF EXCITED PHASE LOCKED

For self excited mode, V and v_i has the same phase, while $v_q = 0$. On the other hand, in self excited phase-locked mode, V is compared to an external reference frequency, and some v_q is introduced to keep the phase of V locked to the phase of the reference, which we can arbitrary assigned to have real part only. Therefore for self excited, whether phase locked or not,

$$v_g = (v_i + iv_q)e^{i\theta} = ve^{i(\theta+\psi)}$$
$$V = \gamma v\cos\phi e^{i(\theta+\phi+\psi)} \qquad (4)$$

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Imaginary part is zero, therefore

$$\theta + \phi + \psi = 0 \quad (5)$$

and

$$\frac{v_q}{v_i} = \tan\psi = -\tan(\theta + \phi) \quad (6)$$

For minimum input power or maximum output voltage

$$\frac{\partial V}{\partial \phi} = -\gamma v \begin{bmatrix} \cos\phi \sin(\theta + \phi + \psi) - \\ \sin\phi \cos(\theta + \phi + \psi) \end{bmatrix} = 0 \quad (7)$$

Or

$$\sin\phi = 0 \,. \quad (8)$$

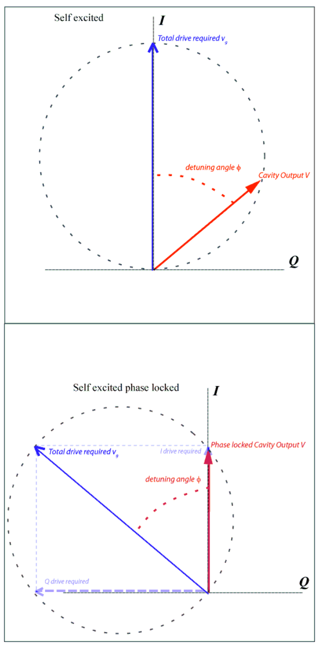

Figure 2: Input and output relationship as a function of detuning angle for self-excited and self-excited phase locked.

To tune the cavity, the cavity is first powered under self excited no phase locked mode. i.e. $\psi = 0$. θ is adjusted for minimum input power. When this is achieved, we have

$$\theta = \phi = \psi = 0 \,. \quad (9)$$

Next the system is phase locked, and the value of ψ will change to maintain $\phi + \psi = 0$. Therefore it is a simple procedure to move the tuner such that the quadrature drive is zero $(\psi \to 0)$ to get $\phi \to 0$, i.e. the condition for minimum power. This algorithm has been implemented in all ISAC-2 superconducting cavities [1].

DUAL CAVITIES SELF EXCITED PHASE LOCKED

Figure 3 shows the block diagram of the dual cavity self-excited loop. The equation is just the vector sum of 2 individual cavities with the same drive.

$$V = \gamma_1 v \cos\phi_1 e^{i(\theta_1 + \phi_1 + \psi)} + \gamma_2 v \cos\phi_2 e^{i(\theta_2 + \phi_2 + \psi)} \quad (10)$$

Let's assume we have tuned each individual cavity individually for minimum input power,

$$\theta_1 = \theta_2 = 0$$

And have adjusted attenuations such that $\gamma \equiv \gamma_1 = \gamma_2$

$$V = \gamma v \left[\cos\phi_1 e^{i(\phi_1 + \psi)} + \cos\phi_2 e^{i(\phi_2 + \psi)}\right] \quad (11)$$

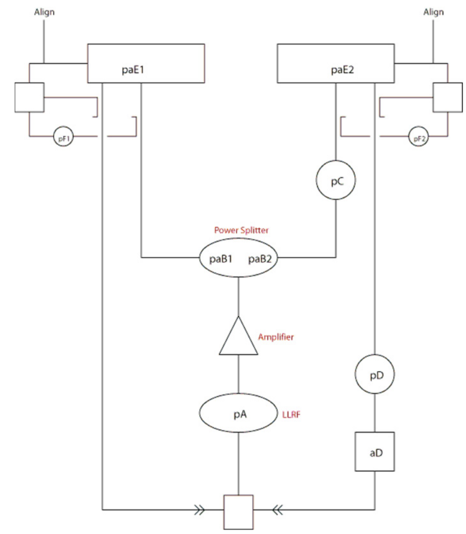

Figure 3: Feedback loop for dual cavities.

Under phase locked condition, the imaginary part of V is zero and is given by

$$\cos\phi_1 \sin(\phi_1 + \psi) + \cos\phi_2 \sin(\phi_2 + \psi) = 0 \quad (12)$$

Rearranging gives

$$\tan\psi = -\frac{(\sin 2\phi_1 + \sin 2\phi_2)}{2(\cos^2\phi_1 + \cos^2\phi_2)} \,.$$

When $\psi = 0$ or $v_g = 0$ $\phi_1 = -\phi_2$ (13)

i.e. when the detuning angles of the two cavities are opposite to each other, the quadrature drive becomes zero. To find the condition for minimum drive, we expand Eq. (13) to

$$|V|^2 = VV^* =$$

$$\gamma^2 v^2 \left[(\cos^2\phi_1 + \cos^2\phi_2)^2 + (\cos\phi_1 \sin\phi_1 + \cos\phi_2 \sin\phi_2)^2\right] \quad (14)$$

Eq. (14) is plotted in Fig. 4. By requiring both

$$\frac{\partial VV^*}{\partial \phi_1} = \frac{\partial VV^*}{\partial \phi_2} = 0 \,.$$

we get,

$$\tan 2\phi_1 = \frac{1}{2} \frac{(\sin 2\phi_1 + \sin 2\phi_2)}{(\cos^2\phi_1 + \cos^2\phi_2)} \,. \quad (15)$$

and

$$\tan 2\phi_2 = \frac{1}{2} \frac{(\sin 2\phi_1 + \sin 2\phi_2)}{(\cos^2\phi_1 + \cos^2\phi_2)} \,. \quad (16)$$

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The only way for both Eq. (15) and Eq. (16) to be satisfied is

$$\phi_1 = \phi_2 = 0 \,. \qquad (17)$$

Eq. 18 gives the condition for minimum drive power. Careful examination of Fig. 4 shows that the local minima of ϕ_1 depends on ϕ_2 and vice versa. This makes tuning difficult if the starting point is some random values of ϕ_1 and ϕ_2. But if we add an additional constraint of $v_g = 0$, then Eq. (15) becomes

$$|V| = 2\gamma v \cos^2 \phi_1 \qquad (18)$$

Therefore we can simultaneously move both tuners to achieve the condition for minimum drive power required by Eq. (17).

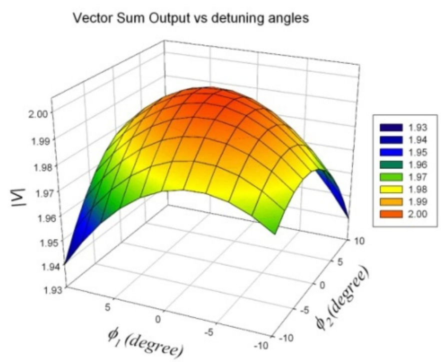

Figure 4. Vector Sum of dual cavity output vs detuning angles.

TUNING ALGORITHM

The initial tuning is done by one cavity at a time, by disconnecting the feedback of the cavity not under tuning. The tuning is performed according to Eq. (10), and the measured ϕ's are stored as the tuner setpoints. The actual tuner setpoints can drift with environment temperature. To reduce disturbance to beam production, retuning can be performed under normal operating condition, i.e. amplitude and phase locked self-excited mode. The steps are illustrated in Fig. 5. Figure 5a shows the initial condition where the two cavities are detuned by $\phi_1 > 0$ and $\phi_2 > 0$ The next step is to move just one of the tuners, in the case Tuner A, to satisfy $\phi_1 = -\phi_2$ [Eq. (13)] such that the quadrature drive is close to zero as in Fig. 5b. If the initial conditions are $\phi_1 > 0$ and $\phi_2 < 0$, we still try to move one tuner to satisfy $\phi_1 = -\phi_2$, changing the direction of movement if the quadrature drive increases instead. Since the measurement of the quadrature drive has a lot of noise, fuzzy logic is facilitate in this movement. Then we can move Tuner B in the same direction but a quarter as much, and reverse the direction of Tuner A and move it by the same amount as shown in Fig. 5c. We can see intermediately the drive power (the vertical line on the left hand side) is significantly reduced. The tuners movements are repeated until the minimum drive is obtained in Fig. 5d. Various methods can be used to achieve the minimum. At present fuzzy logic is used but in the future sliding mode minimum seeking logic will be implemented. After the minimum is achieved, the 2 phase detector setpoints are updated and normal tuning using phase detection method continues. The flow chart for these steps are shown Fig. 6 and is used to generate a script file so that this process can be perform remotely.

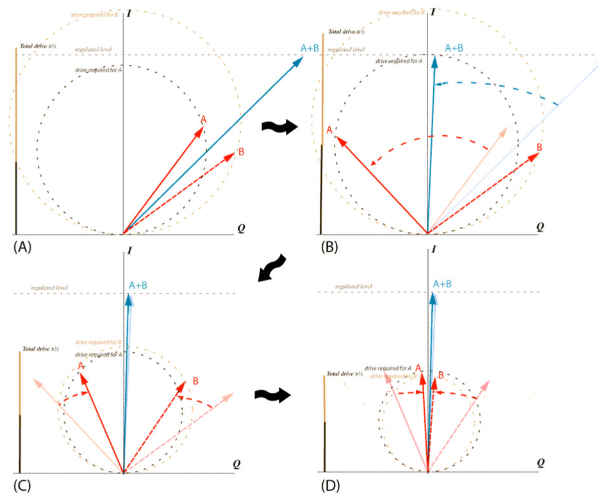

Figure 5: Tuning steps for dual cavities.

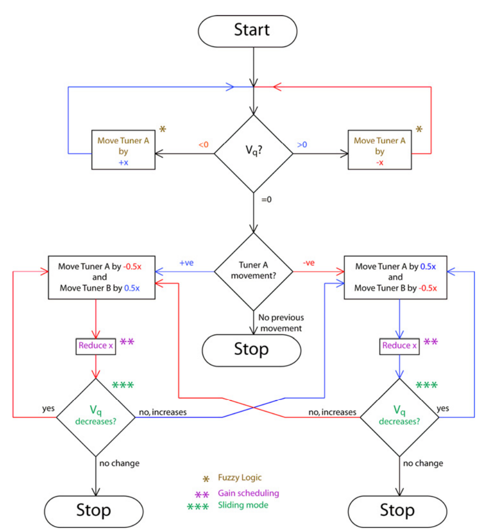

Figure 6: Tuning flow chart for dual cavities.

CONCLUSION

The modified Minimum Qaudrature tuning algorithm has been tested on the elinac ACM dual cavities and has been found to operate satisfactory without any disturbance to beam operation.

REFERENCES

[1] K.Fong, “Minimum Quadrature tuning algorithm for Superconductiong RF Cavity in self excited phase locked mode”, TRI-DN-16-32, 2016.