SELF EXCITED OPERATION FOR A 1.3 GHz 5-CELL SUPERCONDUCTING CAVITY

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Abstract

Self-excited operation of a resonant system does not require any external frequency tracking as the frequency is determined by the phase lag of the self-excited loop, it is therefore particularly useful for testing high Q RF cavities that do not have an automatic tuning mechanism. Self-excited operation has long been shown to work with single-cell cavities. We have recently demonstrated that it is also possible for multi-cell cavities, where multiple resonant modes are present. The Cornell 1.3 GHz 5-cell superconducting cavities were operated using self-excited operation and we were able to lock onto the accelerating π mode, despite the presence of neighbouring modes that were less than 10 MHz away. By means of the loops phase advance, we were able to select which mode was excited.

INTRODUCTION

Self-excited oscillation uses the RF cavity as part of the frequency feedback circuit[1]. Because of this, as long as the loop phase is set up correctly for a cavity powered by self-excited operation, field voltage will develop in the resonator regardless of the mechanical tune of the cavity. In addition, the field voltage is not sensitive to Lorentz force detuning and microphonics as the self excited frequency tracks detuning caused by these effects. This simplifies the powering-up of a high Q cavity, since the cavity's resonant frequency does not need to be determined in advance, making it particularly useful in single-cavity qualifying test. To prevent self-excitation of multiple frequencies in a multi-cell cavity, a combination of bandpass filter and adjustable delay line are used to ensure the self-excited oscillation happens in the desired mode. With the addition of a pair of phase modulator and demodulator, a self-excited loop can be locked to a master oscillator, making it also suitable to be used in a linac.

THEORY

Figure 1 shows the basic elements necessary in a self-excited loop, namely an amplifier and a phase shifter, which are represented as a single block in the figure, a high Q resonator and an amplitude limiter. The resonator and the phase shifter determine the self-excited frequency. The amplitude limiter provides sufficient gain for self-excitation to start. It also provides "capture effect", where it only extracts zero axis crossings of the strongest of competing signals. The strongest oscillation will be captured while rejecting the other. Typically a 3dB difference in signal strength at the input of the limiter is sufficient for the limiter to capture the stronger signal. Transmission lines that interconnect these elements are also included with the amplifier block. At microwave frequencies, where the phase shift of the cascade amplifier/resonator system is difficult to manage, the system is best described using scattering parameters. Using the open-loop cascade method, Figure 2 shows the

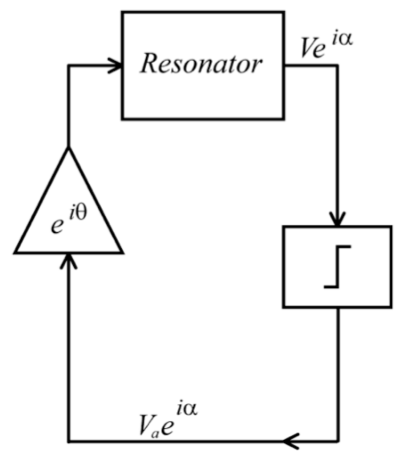

Figure 1: Basic elements of self-excited loop.

same structure as a signal flow graph, with the elements represented by s-parameters. Using Mason's rule, the determinant of the flow graph is:

$$\begin{aligned}\Delta &= 1 - S_{21}S'_{21}\,S'_{21} \\ &- S_{22}S'_{11} - S'_{22}\,S''_{11} - S_{22}S'_{21}\,S''_{11}\,S'_{12} \\ &+ S_{22}S'_{11}\,S'_{22}\,S''_{11}\end{aligned} \quad (1)$$

For transmission lines,

$$S' = e^{-\gamma l}\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix} \quad (2)$$

$$\gamma = \alpha + i\beta$$

where l is the electrical length, α is the cable attenuation and $\beta = \frac{\omega}{c}$ is the propagation delay. Therefore

$$\Delta = 1 - S_{21}S''_{21}\,e^{-\gamma l} - S_{22}S''_{11}\,e^{-2\gamma l} \quad (3)$$

and the forward loop gain is

$$G = \frac{S_{21}S''_{21}\,e^{-\gamma l}}{\Delta} \tag{4}$$

where S''_{21} includes both the cavity and pick-up probe response.

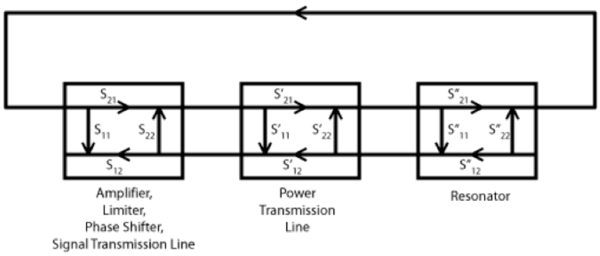

Figure 2: Basic elements of self-excited loops using S-parameters.

The system is unstable and can oscillate without any input when $\Delta = 0$, or

$$\left(S_{21}S''_{21} + S_{22}S''_{11}\,e^{-\gamma l}\right)e^{-\gamma l} = 1 \tag{5}$$

where the first part on the left hand side is due to the complete feedback loop, and the second part is due to the mismatch reflection between the resonator input and the amplifier output. The vector sum represents the actual phase shift around the loop. Without loss of generality, consider the case where a circulator is placed after the amplifier's output, i.e. $S_{22} = 0$, since the mismatch reflections are eliminated, the condition for self-excited oscillation is

$$S_{21}S''_{21}\,e^{-\gamma l} \geq 1 \tag{6}$$

or

$$\left|S_{21}\right|\left|S''_{21}\right|e^{-\alpha} \geq 1 \tag{6a}$$

and

$$\angle S_{21} + \angle S''_{21} - \frac{\omega}{c}l = 2n\pi \tag{6b}$$

Equation 6 states that in order to have self-excited oscillation, the loop gain must exceed unity and the loop phase must be multiples of a wavelength of the resultant oscillation. The function of the amplitude limiter is to ensure the Equation 5 is satisfied at a steady state. In a single-cell resonator, Equation 6b becomes

$$\angle S_{21} + \tan\left(\omega - \omega_p\right)\frac{2Q}{\omega_p} - \frac{\omega}{c}l = 2n\pi \tag{7}$$

When l and S_{21} are selected such that

$$\angle S_{21} - \omega_p\frac{l}{c} = 2n\pi. \tag{8}$$

The self-excited frequency is at the resonant frequency, i.e. $\omega = \omega_p$. At the same time, the capture effect of the amplitude limiter will prevent the system from locking onto the $2(n+1)\pi$ phase as long as

$$Q \geq \frac{l}{\lambda}. \tag{9}$$

This inequality is always satisfied for any normal or superconducting resonant structure. When all these conditions are satisfied, thermal noise and other transients will cascade around the loop as they are being band limited by the resonator. Oscillation will build up, its frequency selected by constructive interference, until the excess loop gain is lost due to the amplitude limiter and the system settles into a steady-state according to Equation 5. The time required to reach steady-state depends on the excess loop gain, but for a superconducting cavity it is dominated by the cavity fill-time.

MULTI-CELL CAVITY

In an N-cell resonator, instead of a single pole response, S''_{21} is given by the multi-pole response[2]:

$$S''_{21}(s) = \prod_{i=1}^{N}\frac{a_i}{\left(s^2 + p_i^2\right)} \approx \prod_{i=1}^{N}\frac{b_i}{\left(s - p_i\right)} \tag{10}$$

Where p_i's are the complex coupled mode resonant frequencies. Equation 6b becomes

$$\angle S_{21} + \sum_i \tan\left(\omega - \omega_i\right)\frac{2Q_i}{\omega_i} - \frac{\omega}{c}l = 2n\pi \tag{11}$$

Again as in the case for single resonator, we adjust l and S_{21} such that

$$\angle S_{21} = \omega_k\frac{l}{c} \tag{12}$$

to select the ω_k mode. Because of the capture effect, only other resonant modes ω_j have sufficiently high $\left|S''_{21}\right|$ and can compete for oscillation, but this still requires that

$$\left(\omega_k - \omega_j\right)\frac{l}{c} + \Phi\left(\omega_j - \omega_k\right) = 2n\pi \tag{13}$$

where $\Phi\left(\omega_j - \omega_k\right)$ is the additional phase shift from S_{21} when operating at ω_j instead of at ω_k. Equation 11 shows that one can choose a $\Phi\left(\omega_j - \omega_k\right) \neq 0$ such that self-oscillation at other modes cannot happen. If a heterodyne system is used, adjustment of the LO causes a corresponding change in the IF, therefore changing the phase shift across the image rejection filter. The image rejection filter also provides additional attenuation at the undesired frequencies so that the inequality in Equation 6a is not satisfied. For example, if an undesired mode is located slightly higher than the desired mode, the LO can be selected such that the self-excited IF is located just inside of the high frequency side of the passband of the image-rejection filter, whereas the undesirable mode's IF is located outside the passband of the filter.

RESULTS OF 5-CELL TEST

The control system of the TRIUMF 1.3 GHz eLinac is based on the successfully design of the ISAC 2 SCRF system [3]. It can operate with an input between 133MHz and 143MHz. The limiting amplifier is an Analog Device AD8306, which offers a dynamic range of 96 dB in this frequency range. The input-referred noise is $1.28nV/\sqrt{Hz}$, equivalent to $4\mu V$ of IF input noise. Coupled with a gain of 96 dB before gain compression, this should provide enough noise for the start-up of self-excited oscillation. The up/down converter to allow the system to operate at 1.3GHz was constructed at Cornell. Only a very rudimentary IF image rejection filter was used, consisting of a 133MHz high-pass filter and a 140MHz low-pass filter. Consequently the IF bandwidth is essentially equal to 10MHz. The test was performed at Cornell using a 5-cell 1.3GHz elliptical cavity. Using a fixed LO frequency of 1160MHz and varying the loop phase alone, we have been able to lock to 3 different cavity modes. This is a direct result of the fact that the IF bandwidth is about 10 MHz wide. The results are summarized in Table 1 and the IF signal of the 1296.5 MHz mode is shown in Figure 3. The other modes have similar responses and are not shown. It should be possible to excite the remaining higher frequency modes by increasing the LO frequency.

Table 1. Different Self-Excited Modes in a 5-Cell Cavity

Mode	LO	IF	RF
1	1160 MHz	129 MHz	1289 MHz
2	1160 MHz	136.5 MHz	1296.5 MHz
3	1160 MHz	139.1 MHz	1299.1 MHz

Most importantly, no mode hopping was observed in the middle of a mode's phase range. Also, because of the large dynamic gain of the limiting amplifier and the wide bandwidth of the IF loop, there was no dead band between the successive modes of operation.

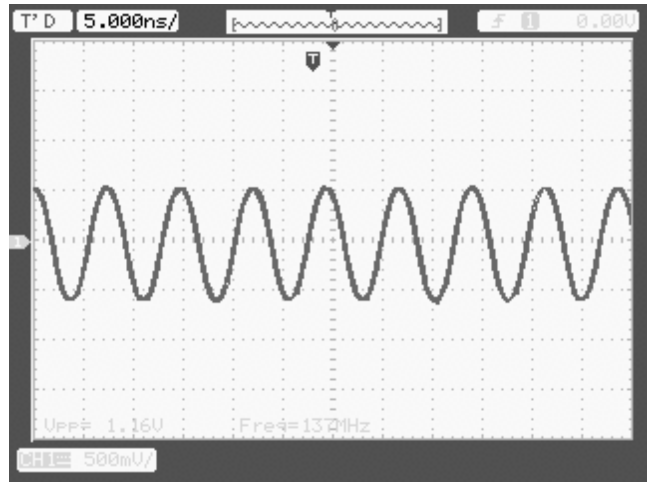

Figure 3: IF signal of 1296.5 MHz self-excited oscillation.

CONCLUSION

We have demonstrated that it is possible for 5-cell cavity to be operated in the self-excited mode. By adjusting the loop phase and the LO frequency, it is possible to lock to any resonant mode of a multi-cell cavity. In the middle of the phase range, stable operation is possible with no mode hopping. Even better performance of the self-excited loop should be possible with a narrow band-pass image-rejection filter, and with better matching of the voltage levels between the TRIUMF-built control system and the Cornell-built up/down converter.

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