ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML082

REFLECTED POWER BASED EXTREMUM SEEKING CONTROL ALGORITHM TO TUNE THE RESONANCE FREQUENCY OF ROOM TEMPERATURE CAVITIES

R. Leewe*, K. Fong, Z. Shahriari, TRIUMF, Vancouver, Canada
M. Moallem, Simon Fraser University, Surrey, Canada

Abstract

Tuning of the natural resonance frequency of an RF cavity is essential for accelerator structures to achieve efficient beam acceleration and to reduce power requirements, as well as for machine protection. Typically, operational cavities are tuned using phase comparison techniques. The phase measurement is subject to temperature drifts and renders this technique labour and time intensive. To eliminate the phase measurement, reduce human oversight and speed up the start-up time for each cavity, this paper presents a control scheme that relies solely on the reflected power measurements. A sliding mode extremum seeking algorithm is used to minimize the reflected power. To avoid tuning motor abrasion, gain scheduling is added to minimize motor movement around the optimum operating point. The system has been tested and is fully commissioned on two drift tube linear accelerator tanks in TRIUMF's ISAC I linear accelerator. Results show that the resonance frequency can be tuned to its optimum operating point while the start-up time of a single cavity and the accompanied human oversight are significantly decreased. Similar results recorded over a 2 month period also show the tuner is able to compensate diurnal temperature variations.

INTRODUCTION

TRIUMF's ISAC I facility is a linear room temperature accelerator which accelerated a CW proton beam.

To achieve efficient beam acceleration and to reduce power requirements, the RF cavities need to be tuned such that the excitation frequency is equal to their resonance frequency. The conventional tuning technique at TRIUMF uses a phase comparison of the input coupler and the output antenna of the cavity [1]. A pick-up antenna provides the phase information and a movable tuning plate changes the resonance frequency by changing the capacitance of the cavity. The phase signal is a high frequency signal and long cables are required to transport the signals from the cavity to the control station. The combination of high frequency signals and long cables renders the phase measurement sensitive to environmental temperature changes. Hence, this technique is only exact when the cables are temperature controlled or the phase shift is accounted for.

As the TRIUMF facility is not equipped with the latter, the phase related difficulties motivated the development of a resonance frequency tuning system based on the reflected power component of the cavity. A system based on the reflected power component also reduces the start up time for each cavity, as the phase setpoint does not have to be empirically adjusted.

Extremum seeking control (ESC) or self-optimization approaches can be traced back to the 20th century. It focuses on control problems where a dynamic nonlinear plant is to be regulated to operate at an optimal operating point or to track an optimal trajectory based on a performance criterion. One of the most robust extremum seeking approaches is sliding mode control which does not require the gradient of the performance function.

This paper presents a sliding mode extremum seeking approach to tune the resonance frequency based on reflected power measurements. This algorithm incorporates a decreasing reference function, which is used to guide the reflected power point to its minimum. At the minimum the reflected power oscillates within a defined vicinity, which is known as the chattering phenomenon. To avoid tuning motor abrasion resulting from the chattering phenomenon the control algorithm is augmented with an adaptive gain which reduces to zero at the minimum operating point. The sliding mode extremum seeking tuning system is implemented in two of TRIUMF's DTL tanks. Long term tuning results show the effectiveness of the tuning scheme and the advantage over TRIUMF's conventional tuning method.

CONTROL ALGORITHM

The reflected power component is a minimum function with a minimum when the resonance frequency equals the operating frequency [2]. Thus, the tuning problem can be rephrased as an extremum seeking problem.

The sliding mode extremum seeking approach features a periodic switching function for real-time optimization of unknown performance functions [3]. In this case we want to minimize the reflected power, thus maximising the field amplitude within the cavity. Given that the dynamics of the system are much faster than the adjustment of the resonance frequency (in the range of seconds), the reflected power can be seen as static map $F(\theta)$. A block diagram of the extremum seeking control with sliding mode and a static map is shown in Figure 1. The switching function is defined as

$$s(t) = F(\theta) - g(t). \tag{1}$$

where $g(t)$ is a time decreasing function satisfying

$$\dot{g} = -\rho, \tag{2}$$

---

* Ramona@triumf.ca

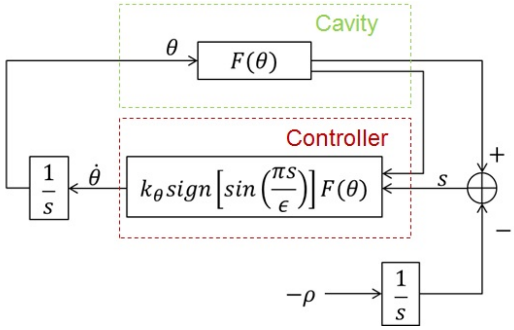

Figure 1: Block diagram: Sliding mode based extremum seeking.

where ρ is a positive constant. The parameter θ is designed to satisfy

$$\dot{\theta} = k_\theta F(\theta) sgn\left[sin\left(\pi s/\epsilon\right)\right], \tag{3}$$

where k_θ is a positive gain. The motor speed $\dot{\theta} = \pm k_\theta F(\theta)$. As the reflected power $F(\theta)$ approaches zero as the tuner position approaches its optimum the motor speed decreases and stops $F(\theta) = 0$.

TUNING RESULTS

The proposed system has been implemented on TRIUMF's room temperature drift tube linear accelerator tanks 4 and 5. The experimental setup was described in [2].

Tuning results for tank 5 and tank 4 are presented in Figure 2 and 3, respectively. The plots display the measured forward and reversed power and the tuning position over 18 hours of operation. Within the first minutes of operation, the forward power is increased to the desired operating point. As the forward power increases the cavity warms up through RF heating, the cavity walls expand and the resonance frequency drifts, yielding an increase in reverse power. The tuner tracks the resonance the resonance frequency drift and adjusts the tuning position accordingly. Figure 2 shows the result of a perfectly critically coupled resonator. After roughly two hours of operation, the cavity temperature does not change anymore, the reversed power decreases to zero and the tuner movement stops. Figure 3, on the other hand, shows a tuning result for a cavity with slightly varying coupling factor, which changes with respect to the resonator temperature. It can be observed that the minimum reflected power value changes over 4 hours of operation. After that, the temperature does not change anymore and the tuner position settles. As the reflected power does not reach zero, the tuner speed $\dot{\theta}$ can not reach zero. yielding small oscillations around the optimum operating point.

Figures 4 and 5 show long term measurement of DTL tank 5 and tank 3, respectively. While the resonance frequency of tank 5 is tuned through the sliding mode system, tank 3 is still tuned through phase comparison [4]. The measured forward power, reversed power, tuner position, and the temperature within the ISAC facility are displayed over 12 days of operation. With respect to Figure 4, it can be observed that the tuner position changes over the course of a day although the input power is constant. The tuner position changes correspond to the environmental diurnal temperature variation. During the peak temperature hours the cavity warms up and expands. The control system counteracts these temperature variations depicted by the wave form like curve of the tuner position. It should be noted that these temperature variations also affect the coaxial cables transporting the cavity signals to the control station. In [5], Czuba and Sikora analyzed the temperature stability of different coaxial cables. They showed that environmental temperature variations influence the delay or the phase of a signal transported through coaxial cable. Figure 5 shows the mentioned effect. While the tuner position adjusts with respect to the temperature variations affecting the cavity itself, it can be observed that the reflected power component of the cavity also oscillates with respect to the temperature. Examining the temperature and reflected power curve, it can be concluded that the phase setpoint of the tuning loop was chosen at roughly 26°C. A deviation of the temperature yields a loop phase error and an increase of reflected power, which is compensated through an increase of the forward power.

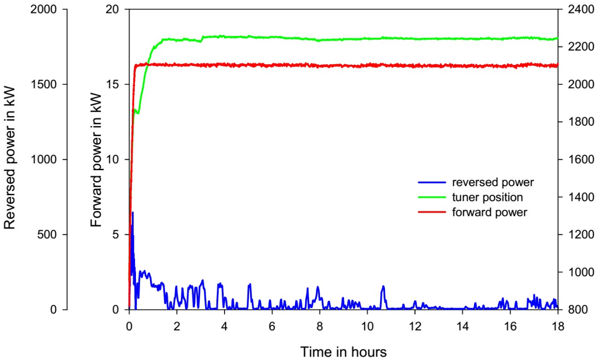

Figure 2: DTL5 reflected power measurement.

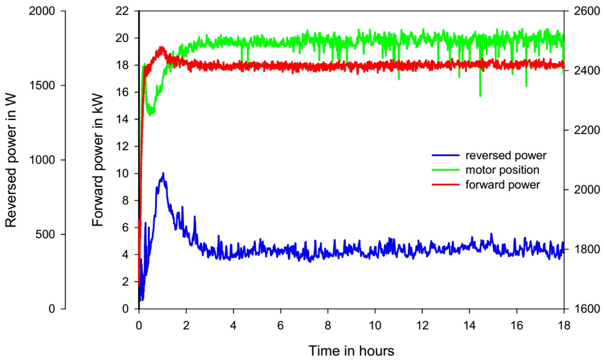

Figure 3: DTL4 reflected power measurement.

The additional phase error also causes problems when starting a cavity which is operated by the traditional phase based tuning system [6].

If one uses reflected power as control variable, this additional error is eliminated since the reflected power is not a high frequency signal and hence temperature insensitive.

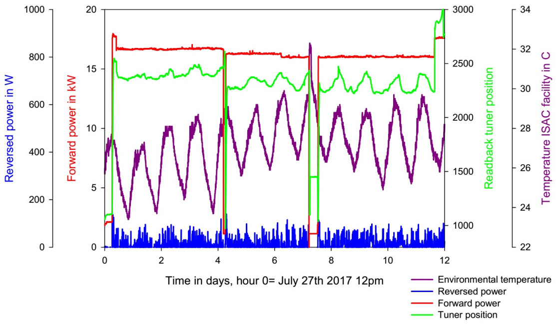

Figure 4: Long term measurement DTL tank 5. Reflected power and sliding mode resonance frequency tuning.

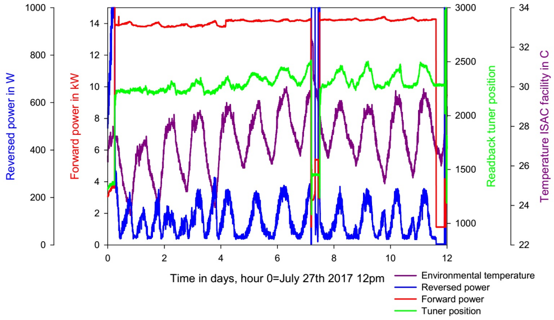

Figure 5: Long term measurement DTL tank 3. Phase comparison and linear control.

CONCLUSION

This paper introduced a control scheme for resonance frequency tuning of an RF cavity which solely depends on the measurement of the reflected power component. The temperature dependent phase measurement and the accompanied problems during the start up are eliminated. This alone reduces the manual required work tremendously. In addition, the system outreaches the conventional tuning system in terms of controllable bandwidth and accuracy. The test result of the commissioned system on the DTL tanks 4 and 5 show its performance under real life conditions. To further reduce human oversight, the system will be commissioned in further room temperature cavities at TRIUMF's ISAC I facility.

REFERENCES

[1] K. Fong, M. Laverty and S. Fang, "RF Control Systems for the TRIUMF ISAC RF Structures," in *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, Il, USA, 2001.

[2] R. Leewe, K. Fong and M. Moallem, "Novel scheme to tune RF cavities using reflected power", in *Proc. 28th Linear Particle Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 757–759, `https://doi.org/10.18429/JACoW-LINAC2016-THOP06`

[3] Y. Pan, U. Ozguner and T. Acerman, "Stability and Performance Improvement of Extremum Seeking Control with Sliding Mode," in *International Journal of Control*, Ohio, OH, 2010.

[4] K. Fong, M. Laverty and S. Fang, "RF control systems for the TRIUMF ISAC RF structures", in *Proc. 2001 Particle Accelerator Conf. (PAC'01)*, Jun. 2001, Chicago, IL, USA, paper MPPH078, pp. 948–950.

[5] K. Czuba and D. Sikora, "Temperature stability of coaxial cable", *Acta Phys. Pol. A*, vol. 118, p. 553, 2011.

[6] K. Fong, S. Fang, M. Laverty, J. Lu and L. Poirier, "Commissioning of the TRIUMF ISAC RF system", in *Proc. 2001 Particle Accelerator Conf. (PAC'01)*, Jun. 2001, Chicago, IL, USA, paper MPPH077, pp. 945–947.