NOVEL SCHEME TO TUNE RF CAVITIES USING REFLECTED POWER*

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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. Typically, operational cavities are tuned using phase comparison techniques. Phase measurement is subject to temperature drifts and renders this technique labor 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 reflected power measurements. A sliding mode extremum seeking algorithm is used to minimize the reflected power. To avoid tuning abrasion, a variable gain minimizes 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. Experimental 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.

INTRODUCTION

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.

Phase detectors cannot be located close to the cavity given that it is also a source of x-radiation. The high frequency nature of the phase signal and the necessary long cable length result in a high temperature sensitivity of the phase. Due to thermal effects on amplifier and cables, phase drifts result in inexact cavity frequency adjustment. The temperature sensitivity also leads to phase drifts outside the controllable range necessitating frequent manual phase adjustment. Consequently, starting up a single cavity and tuning its resonance frequency can take up to several minutes.

The phase related difficulties motivated the development of a frequency tuning system based on reflected power or reflected voltage. Room temperature cavities are operated as critically coupled, in which the operating and resonance frequencies of the cavity are equal, the reflected power is zero, and the acceleration field is at its maximum. When the two frequencies diverge, the reflected power increases. A new method to control the cavity's resonance frequency is based on utilizing the reflected power characteristics [2]. The reflected power is a function with minimum. Hence, the frequency tuning using reflected power measurement can be rephrased as an extremum seeking problem.

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 the application of a two time scale sliding mode extremum seeking algorithm to minimize the reflected power. An adaptive gain stops the motor movement in the vicinity of the optimum to eliminate small oscillations around the driving frequency and to reduce motor setup abrasion. Experimental tests were performed on TRIUMF's drift tube linac (DTL) tank 4 and 5.

CAVITY FIELD AND REFLECTED POWER

The cavity behavior can be described by a parallel resonant circuit [3]. The corresponding differential equation in terms of the reflected voltage and under perfect impedance matching condition is stated as [2]

$$\ddot{z} + \gamma \dot{z} + \left(\omega_0^2 + k\theta\right) z = V_f cos\left(\omega_i^2 - \omega_0^2 - k\theta\right). \quad (1)$$

The relevant variables and parameters are defined as follows:

z reflected voltage;
γ damping coefficient;
ω_0 geometry dependent natural resonance frequency;
V_f forward input voltage amplitude;
ω_i operating frequency;
θ control input;
k tuning sensitivity in terms of $\frac{Hz^2}{mm^2}$

Application of a control input θ to the tuning system of the cavity changes the capacitance of the cavity, which in turn affects the natural resonance frequency of the cavity. The solution to (1) in terms of transient and steady state components as well as the analytical form of reflected signal, $z(t)$, is provided in [2]. The measured reflected power $F(\theta)$ is obtained through the rectified reflected signal, which can be mathematically modeled by a low pass filter as follows

$$F(\theta) + \tau \dot{F}(\theta) = z^2, \quad (2)$$

where τ denotes the time constant of the low pass filter. The reflected power can then be mathematically expressed as

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follows

$$F(\theta) = \frac{1}{2}V_f^2 \frac{\left(\omega_0^2 + k\theta - \omega_i^2\right)^2}{\left(\omega_0^2 + k\theta - \omega_i^2\right)^2 + \gamma^2\omega_i^2}. \qquad (3)$$

The steady state ideal reflected power function $F(\theta)$ has a minimum of zero when operating and resonance frequency are equal, $\omega_0^2 - \omega_i^2 + k\theta = 0$ as shown in fig 1.

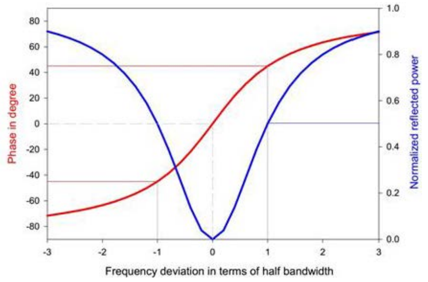

Figure 1: Normalized reflected power versus the frequency deviation in terms of half system bandwidth.

CONTROL ALGORITHM

The idea of the two time scale sliding mode extremum seeking approach relies on the introduction of a control parameter rather than the control input itself while a preselected stabilization controller is already in the loop [4]. The acceleration structure is a stable system and does not need to be stabilized, hence, only a extremum seeking controller is required. In general, the sliding mode extremum seeking approach features a periodic switching function for real-time optimization of unknown performance functions [5]. 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 $F(\theta)$, see Fig. 1. A block diagram of the extremum seeking control with sliding mode and a static map is shown in Fig. 2. The switching function is defined as

$$s(t) = F(\theta) - g(t). \qquad (4)$$

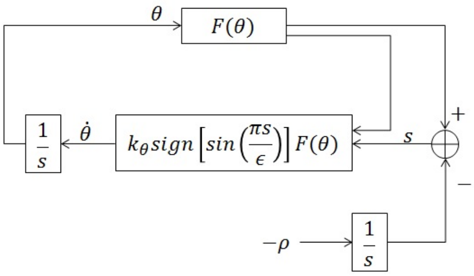

Figure 2: Block diagram: Sliding mode based extremum seeking.

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

$$\dot{g} = -\rho, \qquad (5)$$

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

$$\dot{\theta} = k_\theta F(\theta) sgn\left[sin\left(\pi s/\epsilon\right)\right], \qquad (6)$$

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 $F(\theta) = 0$.

SYSTEM COMMISSIONING ON TRIUMF'S DTL TANKS 4 AND 5

The proposed system has been implemented on TRIUMF's room temperature drift tube linear accelerator tanks 4 and 5.

A block diagram of the experimental setup is shown in fig 3. A four-axis motion controller (DMC-2123, Galil Motion Control, Inc., Rocklin, CA, USA) is used for the algorithm implementation, with the input of the measured forward power, reflected power and to drive the tuner plates, thus changing the resonance frequencies of the two tanks. The measured forward power is used for normalization of the reflected power. The control scheme, equation (4), (6), is implemented on the 32-bit processor embedded in the motion controller. The program is written using DMC Smart Terminal software in the specific Galil command language. The cavity is operated as a generator driven resonator and driven by an external driven RF reference frequency. A directional coupler is used to pick up a small portion of the reflected and forward power.

The mechanical tuning setup is adopted from the previous cavity tuning using the conventional phase comparison technique. It is composed of a stepper motor with a translated rotational movement into a linear movement. The mechanical setup provides a resolution of 15Hz per step, which corresponds to the accuracy of the tuning system.

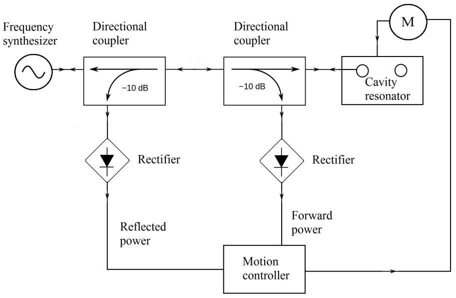

Figure 3: Block diagram of the mechanical setup.

TUNING RESULTS

The reflected power measurement results are displayed in Fig. 4 and 5, respectively for DTL tank5 and tank4. Figure 4 shows a test result for an ideal critically coupled cavity.

In the beginning within the first 10 minutes of operation, the forward power is increased up to 16 kW (red line), the desired operating power. The reflected power (blue line) increases to roughly 400W as the cavity warms up and the cavity expands, which is called *RFheating*, and the resonance frequency diverges from the operating frequency. The tuning position (green line) adjusts quickly and tracks the operating frequency. It can also be observed that the tuning position is tracked constantly and changes up to $1\frac{1}{2}$ hours until it settles, the reflected power decreases to zero, and the motor movement stops. The long time span results from the cavity heating. After $1\frac{1}{2}$ hours the temperature does not change anymore, the perfect operating point is reached and the reflected power decreases to zero. DTL4, Fig. 5 shows a similar behavior with the main difference that the reflected power does not reach zero. The coupling factor of DTL4 changes within the first 4 hours of operation, yielding a minimum reflected power greater than zero. After roughly 4 hours the cavity 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.

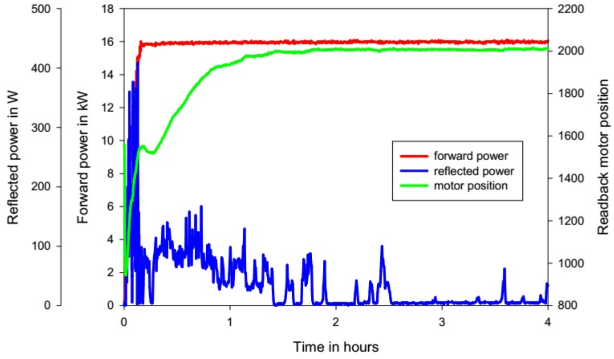

Figure 4: DTL5 reflected power measurement.

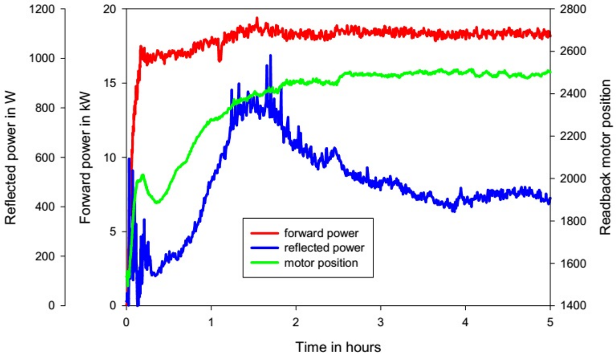

Figure 5: DTL4 reflected power measurement.

Figure 6 shows a long term measurement of DTL 5. The measured forward power, the tuner position and the environmental temperature are displayed over 10 days. It can be observed that the tuner position changes over a course of a day although the input power is constant. The tuner position changes correspond to the environmental temperature changes. 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 cables. As against phase measurements the reflected power measurements are not affected by the environmental temperature fluctuations yielding an overall higher accuracy.

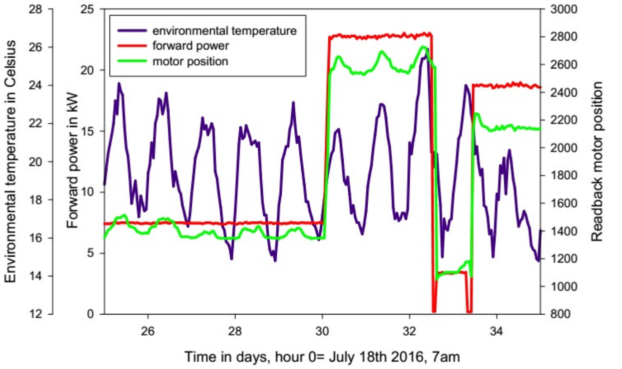

Figure 6: Tuner position depending on set point and environmental temperature.

CONCLUSION

The test results show that a tuning system based on reflected power measurements and the proposed sliding mode extremum seeking algorithm can track the operating frequency and provide optimal operating performance without using phase information and the accompanied manual adjustment. Labour hours connected to the traditional phase comparison technique can be drastically decreased while optimal performance in the long run is guaranteed, as the reflected power measurements are not affected by environmental temperature variations.

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