DOE/ER/40150--326 CONF-950512--367

AUTOMATED FREQUENCY TUNING OF SRF CAVITIES AT CEBAF*

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CEBAF-PR--95-015

Abstract

An automated cavity tuning procedure has been implemented in the CEBAF control system to tune the superconducting RF (SRF) cavities to their operating frequency of 1497 MHz. The capture range for coarse tuning algorithm (Burst Mode) is more than 20 cavity bandwidths (5 kHz). The fine tuning algorithm (Sweep Mode) calibrates the phase offset in the detuning angle measurement. This paper describes the implementation of these algorithms and experience of their operation in CEBAF control system.

I. Introduction

The 338 superconducting RF cavities that populate the linear accelerator at CEBAF need their resonance frequencies tuned to within a few Hertz of the site's 1497 MHz reference oscillator. The resonance frequency of cavities change due to factors such as change in ambient temperature and helium pressure variation.These cavities are tuned using an automated process, known as Autotune, which involves a series of steps: Burst Mode is used to coarsely tune the cavity, starting as much as 5 kHz from center to within ±160 Hz of the operating frequency. Next, Sweep Mode measures the phase offset in the detuning angle measurement to within $\pm 3^0$. Finally, Autotrack mode brings the operating detuning angle to within $\pm 3^0$ of the measured center frequency, and maintains it within $\pm 10^0$ in the presence of system drifts. Various modules of Autotune software run as a single or multiple copies of a Unix process executing on a cluster of HP 9000-7xx workstation(s).

II. Coarse Tuning (Burst Mode)

In this procedure, a bandwidth limited, pseudo-random phase modulated drive signal (noise burst) is sent to the cavity and the response of a 360° phase detector is measured and recorded. A signal from the master oscillator $V_1(t) = |V_1|e^{-iw_0 t}$ is sent to a vector modulator where it is modulated by a pseudo random signal $x(t) = e^{i\phi(t)}$ such that power spectrum of $x(t)$ is a positive constant for frequencies within ±5 kHz and zero outside this range. The output signal from the vector modulator is amplified and sent to the cavity. The cavity acts like a filter on the noise signal and transmits the frequency components close to its resonance. A pickup probe in the cavity responds to the accelerating field, $V_c(t)$, in the cavity. This signal is fed into the 360° phase detector where it is multiplied by a second reference signal, $V_2(t) = |V_2|e^{iw_0 t}$, from master oscillator to produce a baseband output signal $y(t) = V_2(t)V_c(t)$. The cavity resonance frequency can be determined by proper processing of the power spectrum of the output signal $y(t)$ as described in Ref [1]. The Fourier transform of $y(t)$ is

$$Y(w) = \int_0^T y(t)e^{-iwt}dt$$

and it can be shown from reference[1] that

$$|Y(w)|^2 = \int_{-T_M}^{T_M} e^{-iw\tau}T_M\left(1-\frac{|\tau|}{T_M}\right)\langle R_{yy}(\tau)\rangle_T d\tau$$

$$\approx \int_{-\infty}^{\infty} W_{T_M}(\omega-\omega')S_{yy}(\omega')d\omega'$$

where $\langle R_{yy}(\tau)\rangle_T$ is the finite time correlation function and $S_{yy}(\omega')$ is the power spectrum of the output process $y(t)$. The above expression of $|Y(w)|^2$ corresponds to viewing the actual power spectrum through a spectral window W_{T_M}. When the resolution of $|Y(w)|^2$ is within the bandwidth of ±5 kHz the power spectrum of the input process, $S_{xx}(\omega)$ is smoothed resulting in a clean well behaved peak of $|Y(w)|^2$ which is centered around the cavity resonance frequency. Fig 1 shows an example of one such power spectrum obtained while tuning a cavity which was detuned by approximately 2 kHz. The implementation of this technique is described in this section below.

The communication and control of a single SRF cavity is done by an embedded RF microprocessor [2]. This microprocessor is controlled by an EPICS state machine. In Autotune procedure, a preparatory setup of the RF system is completed and 200 Watts of forward power is established before the noise burst is sent down to excite the selected cavity.

The functionality of Burst Mode is described below:

a) Send a trigger signal to the RF microprocessor to generate the noise burst in selected cavity(ies). Wait for acknowledge signal indicating successful completion of Burst Mode.
b) Once the acknowledgment has been received, upload the data from the RF microprocessor to analyze it and determine the cavity resonance frequency.
c) Initiate the tuner stepper motor movement in order to move the cavity resonance frequency closer to the operating frequency.
d) Repeat steps b) through d) until the cavity resonance frequency is within ±160 Hz of the operating frequency of

*Supported by U.S.DOE Contract DE-AC05-84-ER40150

1497 MHz.

e) Constantly check that RF power stays on while going through steps a) to d). If RF power is shut off (due to interlock trips) or if RF module becomes unavailable to the tuning process or if the cavity response signal is lower than the noise threshold ($4 mV/\sqrt{Hz}$) then stop the tuning process after raising appropriate error flags.

The hardware presently used allows the measurement of cavity frequency in a range of up to ±5 kHz from the operating frequency. If the cavity is detuned by several bandwidths, the detuning angle cannot be determined accurately due to low signal to noise ratio of the detuning angle phase detector (i.e. transmitted power is low). A typical Burst mode power spectrum is shown in figure 1. This cavity was detuned by approximately 2 kHz.

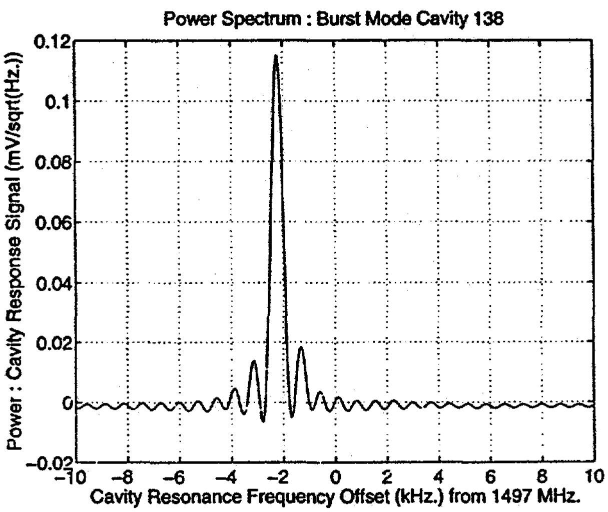

Fig 1

III. Fine Tuning (Sweep Mode)

In this procedure an analog feedback loop stabilizes the accelerating gradient in the cavity at 3 MV/m. A single side band modulation of the operating frequency is generated using the phase offset vector modulator. The phase offsets both in X and Y direction are set using $V_x = V_0 \sin(2\pi f_m t)$ and $V_y = V_0 \cos(2\pi f_m t)$. Ten points in one period of the modulating frequency are sufficient to suppress the lower order harmonics. The time interval between two DAC settings is given by $dt = 1/(f_m \times n)$, where n is the number of points in one 360° period. The detuning angle is constantly measured during the sweep process, and averaged to suppress dependence on microphonic noises. The modulating frequency is swept over the range of ±200Hz in steps of 5Hz

The detuning angle measurement and the modulating frequency sweep are related as described by

$$\varphi_{meas} = \mathrm{atan}\left(2 \times Q_L \times \frac{f_m}{f_o}\right) + \varphi_{off}$$

where, φ_{off} is the offset between measured detuning angle from the hardware and the actual detuning angle. Q_L is the loaded quality factor for the cavity. The frequency sweep of ±200 Hz in steps of 5 Hz takes 80 seconds. The sweep data is then uploaded from the RF microprocessor for analysis. The uploaded sweep data contains the detuning angle measurement from the hardware versus the modulating frequency data. A nonlinear curve fit is performed on this data to extract the detuning angle offset, the loaded quality factor and the cavity operating frequency. If the curve fit does not succeed to within the specified tolerances, then an alarm is raised and tuning process is terminated. A plot of the measured detuning angle data versus the modulating frequency and a nonlinear curve fit is shown in figure 2.

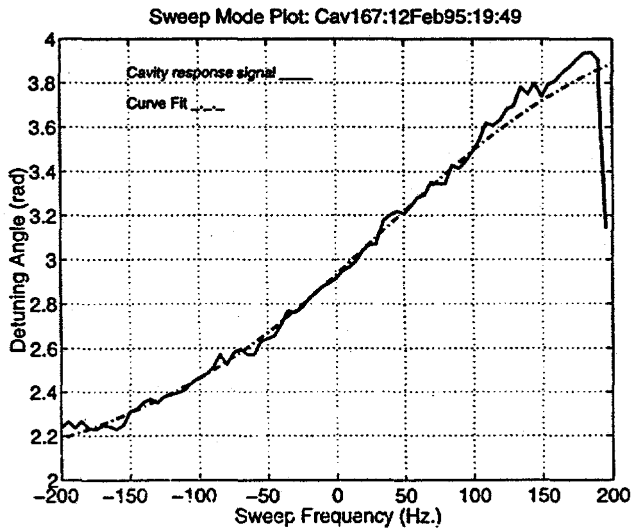

Fig 2

The detuning angle offset determined by the Sweep Mode is passed on to another process called Autotrack, which maintains a tuned cavity on resonance. Autotrack constantly monitors the measured detuning angle. A non-zero detuning angle means that cavity has drifted. The sign of the angle is an indication of which direction the stepper motor should be moved to compensate for the drift. Autotrack starts to move the stepper motor when it detects a detuning angle of greater than $\pm 10^0$ and continues to move the stepper motor until the detuning angle is within $\pm 3^0$. The response speed of the Autotrack feedback loop is designed to minimize the chances of overshoot, since recovering from overshoot involves unwinding the gear train backlash. One goal is to minimize the total motion of the stepper motor, since there are reliability concerns for the vacuum feedthrough that carries the drive shaft to the superconducting helium bath.

IV. Operational Experience

The Autotune routine has been used to tune SRF cavities at CEBAF since April 1994. Prior to availability of this facility, the cavities were tuned manually using a network analyzer and a stepper motor controller box. The cavity to be tuned was subjected to a frequency sweep using the network analyzer and the amplitude of measured gradient signal from field probe in the cavity was observed to detect the cavity resonance frequency. Then the tuner stepper motors were moved using the controller box to tune the cavity to a resonance frequency of 1497 MHz. This process was not considered practical for long term routine use for a full complement of 338 cavities.

All of the cavity tuning now is done using the Autotune routine. The user interface for Autotune is based on the EPICS display tool MEDM. A diagnostic user interface is also provided, which is based on Tcl/Tk programming language. The diagnostic interface provides the ability to view the power spectra during Burst mode tuning and the sweep mode plot and the progress messages that are generated during the tuning process.

Performance statistics for Autotune routine were obtained from the logfiles that are created during the tuning process. The Autotune facility was used 1933 times during a three month period of 1/95 to 4/95. CEBAF has 338 SRF cavities. Thus, on an average a cavity was tuned approximately 6 times during this three month period.

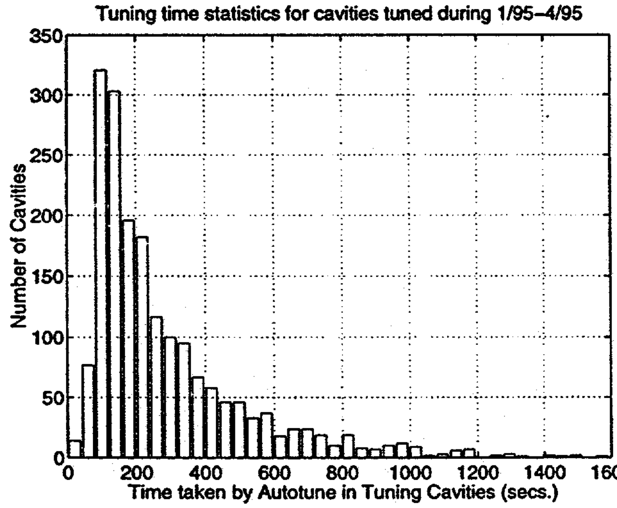

Fig 3

The figure 3 shows a histogram of the time taken by the tuning process. A majority of the cavities were tuned within ±160 Hz of operating frequency in less than 150 seconds. A few cavities took as long as 1600 seconds to be tuned. Some of these cavities are known to have a considerable backlash in the gear train driven by the stepper motor to squeeze or expand the cavities. A few other cavities have sticky gear trains. The tuning time is also proportional to the amount of offset between cavity resonance frequency and the desired operating frequency. Some of the cavities that took a long time to tune were detuned by almost 5kHz.

Figure 4 shows a histogram of detuning offset in cavity resonance frequency before Burst Mode tuning. A majority of cavities were detuned by -0.5 kHz. Burst Mode detected a few cavities within a range of ±10 kHz which exceeds the specification on operating range of Burst Mode set at ±5 kHz.

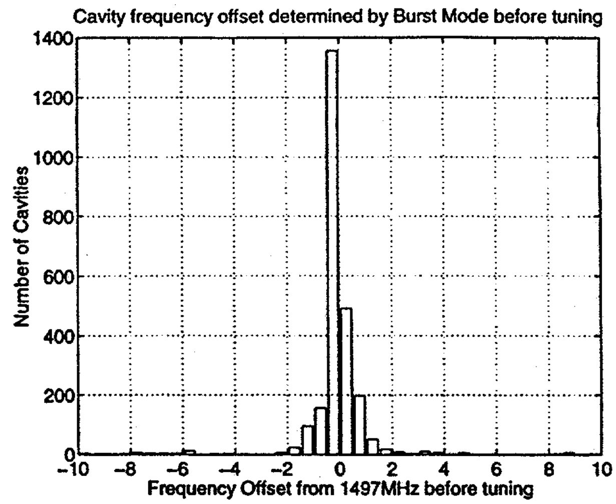

Fig 4

Figure 5 shows a histogram of the cavity resonance frequency offset from the operating frequency after Burst Mode tuning was completed. All the cavities were tuned to within ±160 Hz specification for coarse tuning. A majority of cavities tuned appear to have been detuned by negative offset. This can be attributed to positive pressure fluctuations in the helium pressure during cryogenic testing that took place during this three month period.

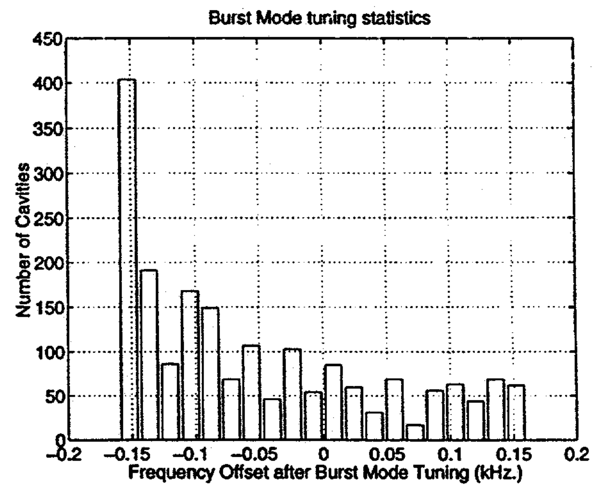

Fig 5

VI. REFERENCES

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[2] "Microprocessor Support for CEBAF RF Control Module," I. Ashkenazi and G.E. Lahti, Proceedings of 1989 PAC Conference, pp 1861

[3] "Software Requirements for RF Autotune," M. Chowdhary, J. Tang, Controls Software Group Requirements Document, CEBAF, 22 February 1994.

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