Frequency-feedback Tuning for Single-cell Cavity Under RF Heating*

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Abstract

A tuning system is described that is being used to match the source frequency of a high-power klystron on the resonant frequency of the prototype single-cell cavity for the 7-GeV Advance Photon Source (APS) storage ring. Typically a water-cooled piston tuner is required to adjust the reactive component of the cavity's impedance to minimize reflected power back to the RF drive source. As the cavity walls expand due to RF heating, the resonant frequency decreases. Adjusting the source frequency to follow the cavity resonant frequency is a convenient method used to condition the cavity (for vacuum) at high power levels, in this case, 1 MV gap voltage at 100 kW power level. The tuning system consists of two coupling ports, a phase detector, a digitizing I/O system, and a DC coupled FM-modulated RF source. Proportional Integral Derivative (PID) loop parameters for the Experimental Physics and Industrial Control System (EPICS) software are calculated, and data is presented showing the damped response to perturbations on the loop.

The tuning system presented here does not need water-cooling, has no moving parts to wear out, and has an inherently faster response time. Its one limitation is the digitizing sampling rate. The only limitation in tuning range is the bandwidth of the RF source.

I. INTRODUCTION

A block diagram of the RF system is shown in Figure 1. That portion of the RF test stand controlling the amplitude and phase of the RF in the single-cell cavity being tested is described below. Also included is a description of the phase regulation that maintains the cavity's resonance point. Both pulse and continuous wave (CW) operation are supported to allow connection and testing of various high-power components.

The single-cell cavities being designed for the APS storage ring will require RF input power of 57 kW and 800 kV gap voltage each at a nominal frequency of 352 MHz to maintain a 200 mA, 7.5 GeV stored beam [1]. The engineering design is 1 MV.

A cavity resonance-control loop is used to match the source frequency of a high-power klystron with the cavity's resonance frequency. The loop modulates the RF frequency to track the resonant frequency of the RF cavity load under RF heating if a tuner is not used. In operating accelerators, a control loop adjusts a water-cooled mechanical tuner slug through a stepper motor to match the cavity's resonant frequency with the RF source frequency to satisfy any beam loading requirements, as well as minimize reflected power back to the high-power RF source. Temperature regulation of the cavity structure has been used for the purpose of thermal detuning correction [2].

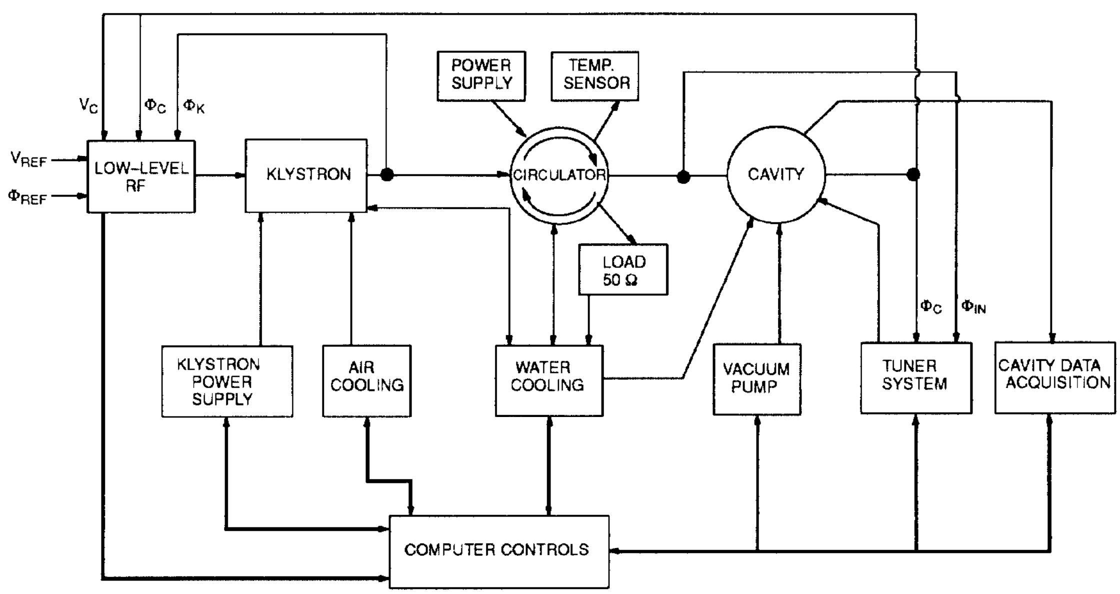

Figure 1. Resonance control setup of the RF test stand.

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Under CW operation the cavity will heat up causing the resonant frequency to shift. If a tuner is not installed, then the RF source frequency can be modulated to follow the cavity's resonant frequency. The frequency will track until the maximum frequency deviation is reached. Past this point, the cavity will begin to detune. When a preset value of VSWR is reached, the reverse power will trip off the RF drive. This can be prevented by changing the RF source frequency by an amount equal to the maximum deviation. The inherent fast response of this method is a convenient way to vacuum condition the cavity at high power levels.

II. DESCRIPTION

For cavity tuning control, a feedback system is used to compare the cavity phase with the input phase, from a waveguide coupling port, and adjust the tuner system to keep the cavity at the resonant frequency within +/– 1°. The two signals are compared with a digital phase meter to produce an error signal. A phase shifter is inserted in the cavity input power signal to set the cavity phase at the resonance frequency near zero. The digital phase information is read by a microprocessor located in the slot 0 controller card of a VME crate, which then adds the required phase offsets, producing an error signal to control the frequency of the RF source.

The digitizing I/O system modulates the synthesizer with a frequency offset to follow the cavity's resonant frequency changes under RF heating, without the need for a water-cooled mechanical tuner system. The bandwidth of this system is limited by the modulation bandwidth (50 kHz) and the maximum FM deviation (in this set-up, +/– 100 kHz) of the RF source.

The loop corrects only the reactive element of cavity input impedance by keeping the phase difference between the RF input and field probe at a constant value.

For this instance where the cavity does not have a mechanical tuner, the frequency of the RF source will be modulated by a DC-coupled voltage under computer control to track the resonance point of the cavity as it drifts due to RF heating.

III. RESONANCE LOOP PARAMETERS

The cavity's phase sensitivity is

$$\frac{90°}{3\ \mathrm{dBBW}} = \frac{90°}{17\ \mathrm{kHz}} = 5.3\ \frac{\mathrm{mDeg.}}{\mathrm{Hz}}.$$

The A/D and D/A converters used were 12-bit VME modules in the controller crate. The A/D resolution over its input voltage range of +/– 10 V limits the phase error of the cavity to

$$\frac{\pm\ 10\ \mathrm{V}}{12\ \mathrm{bits}} = 4.8\ \frac{\mathrm{mV}}{\mathrm{bit}} \mathrm{x} \frac{0.1°}{\mathrm{mV}} = \frac{0.48°}{\mathrm{bit}}.$$

The modulation sensitivity is defined by the modulation index of the RF source and was set to +10 kHz/V for initial loop tuning and then the full +100 kHz/V deviation for operation.

A proportional integral controller (PI) sets the feedback function of the resonance tracking loop. Its easy tuning and offset adjusting allowed quick closed-loop operation. The feedback system is shown graphically in Figure 2.

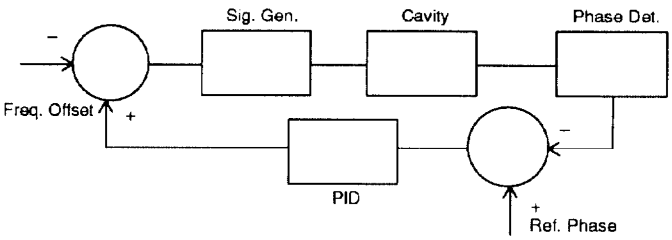

Figure 2. Gain line–up.

The transfer function of the feedback loop is calculated, from the frequency deviation voltage to the phase detector voltage, to be

$$\beta = \frac{+\ 100\ \mathrm{mV}}{+\ 100\ \mathrm{kHz}} \mathrm{x} \frac{1\ \mathrm{Hz}}{5.3\ \mathrm{mDeg}} \mathrm{x} \frac{+\ 1°}{+\ 10\ \mathrm{mV}} = 0.189.$$

The FM bandwidth of the RF source is 50 kHz at 1 dB. The scan rate of the A/D and D/A is set by the program to be a maximum of 10 readings/sec. The phase detector's output has a 3rd-order elliptic filter with a 3-dB bandwidth of 800 Hz and a rise time of 334 us.

IV. PID PARAMETERS

The Ultimate tuning method [3] was used to set the PI parameters in the EPICS software. The ultimate gain (Su) is the value of KP needed to sustain oscillations about the set point value. The ultimate period (Pu) is the period of sustained oscillation. A rule of thumb for controllers of the form Kc(1 + 1/Tip + Tdp) using proportional plus reset control is Kc=0.45 Su, and Ti=Pu/1.2. In the EPICS software PID control algorithm, the change in error function (or velocity algorithm) has the form

$$\mathrm{DM} = \mathrm{KPx(de)} + \mathrm{exdtx}\,\frac{\mathrm{KI}}{60} * \mathrm{KP} + \left(\frac{\mathrm{de}}{\mathrm{dt}} - \frac{\mathrm{dep}}{\mathrm{dtp}}\right) * \frac{\mathrm{KD}}{60} * \mathrm{KP}.$$

Therefore, the program values for proportional plus reset control are KP=Kc=0.45Su, KI=60/Ti=72/Pu.

A proportional integral derivative controller (PID) could have been used to offset the dead time caused by the 10-Hz scan rate of the A/D and D/A and provide a faster response. However, the initial tuning would be much more difficult and was not pursued. A procedure is given in Ref. [4].

V. OPERATION

Before the loop is run in a closed loop, the phase offset of the cavity must be adjusted to compensate for cable differences. This value then becomes the reference for the loop. The procedure used is the following:

a. Set klystron output power to below 1 kW to minimize RF heating.
b. Turn off signal generator modulation.
c. Adjust signal generator frequency until reflected power is a minimum (<–15 dB).
d. Read phase value on vector voltmeter.
e. Record as phase offset value.

With KI=KD=0, KP was set to sustained oscillation of phase difference after a step input of 1 kHz in frequency in a closed loop mode with the RF source modulation index set initially for 10 kHz deviation. This was done to keep the reflected power small.

The ultimate gain and period were found to be Su=1.47 and Pu=0.625 seconds. Once the loop was optimized, the RF source deviation was set to a maximum to allow increased tuning for higher RF power. Scaling the PID parameters for maximum source frequency deviation, KP only was changed to 0.2.

Figure 3 shows the response of the resonance tracking loop due to perturbation of 1 kHz in the PID setpoint. This data was taken for KP=0.1, KI=10000, SCAN=0.2, and the RF source deviation set to 10 KHz.

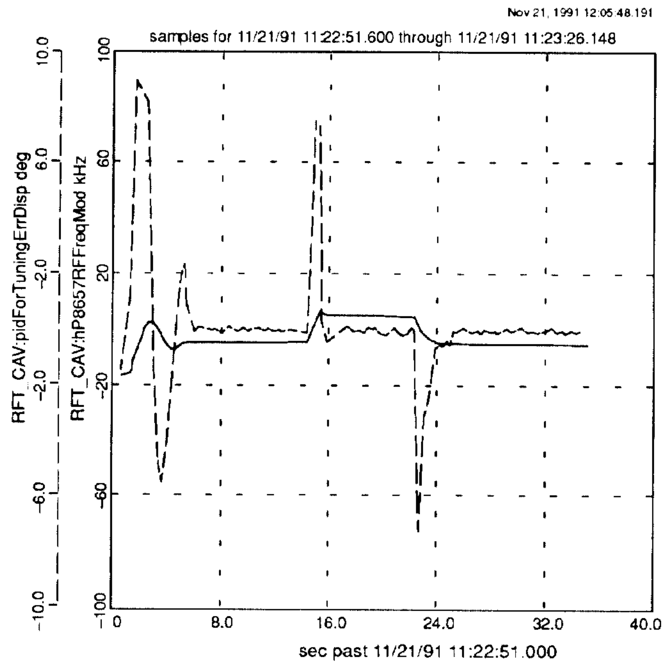

Figure 3. Closed-loop response for KP=0.1, KI=1000.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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