RHIC/RF-26

RHIC Project

BROOKHAVEN NATIONAL LABORATORY

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26.7 MHz Cavity Mechanical Tuner Requirements

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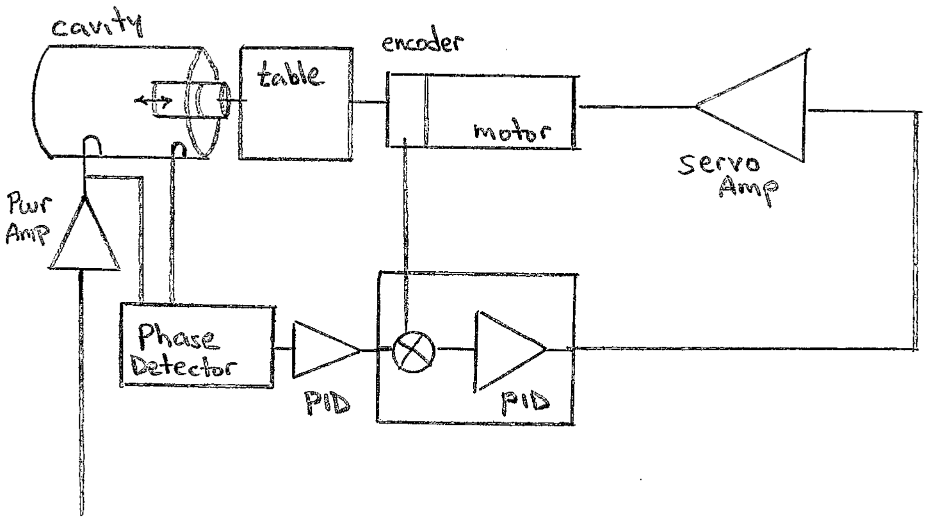
The following note describes the performance limits of a mechanical tuner as dictated by the mechanical constraints. It should be noted that these are the hardware limits. These brute force numbers will be tamed on the one hand by the PID controller and by finessing the manipulations to minimize the perturbation of the beam.

The system analyzed is the PoP mechanical tuner driven by a commercial DC servo system made by AeroTech, shown schematicaly[1] in the figure below, with the following specifications:



AeroTech ATS 02005 table with 4mm leadscrew;
160mm/s maximum table velocity;
Table weight 2.2 kg;
Motor peak torque Tp=2.52N-m;
Rotor inertia Ja=5.7×10^{-5}kg-m^2.

The load calculations are based upon a 11.4 kg tuner;
2.2kg table;
3.2kgf spring constant and
3.2 kgf vacuum force
(1 kgf = 9.8 Newtons)

I) Peak acceleration

The total torque must equal the frictional torque and the acceleration torque;

$$T_{total} = T_{frictional} + T_{acceleration}$$

where

$$T_{frictional} = \frac{Force * Lead}{2\pi\eta} = \frac{6.4\,Kgf \cdot 0.4\,cm}{2\pi(.9)} = 0.45\ Kgf\text{-}cm$$

and

$$T_{acceleration} = J_{total} * \dot{\omega}$$

The total inertia is the sum of the motor inertia, lead screw inertia and load inertia. The load and screw inertias are calculated as

$$J_{screw} = \frac{\pi \gamma L d^4}{32 * g}$$

and

$$J_{load} = \frac{weight}{g} * \frac{l}{2\pi}^{2}$$

where L is the screw length, g gravitational constant, γ is the density in g/cm^3, d is the screw radius in cm, and l is the lead of the screw in mm/revolution. For ease of calculations using the motor data the inertia's are expressed in terms of the obscure units of kg-cm-sec^2 by dividing by the gravitational constant.

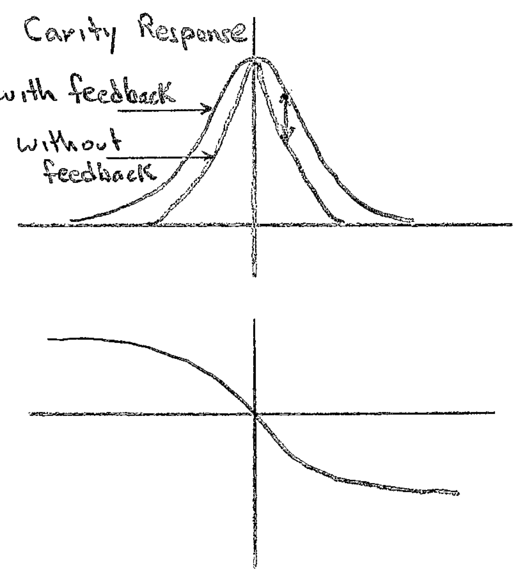
Thus

J_{motor} (5.8X10^{-4}) + J_{screw} (7.9x10^{-6}) + J_{load} (5.6x10^{-5}) =J_{total} = 6.4x10^{-4}kg-cm-sec^2.

Solving for the acceleration in the torque equation we arrive at the peak acceleration of 40,180 rad/sec^2.

II) Required Accuracy

The beam must see phase errors of less than 0.15 degrees^2 in order to keep emmittance growth due to the errors below 1%. The cavity will have local feedback closed around the tuning loop which will have a gain of 100, this reduces the tolerance within the feedback to 15 degrees.



In this case the power amplifier must be able to provide the additional power. At 15° off the peak of the resonance the cavity voltage drops by V=Vo cos 15, or 0.966Vo. Since the power required goes as the square of the voltage or .966^2, P=1.07Po, which is well within the reserve of the amplifier. In order to give adequate margin for the design of the tuner we will use a 7.5° accuracy requirement for the subsequent calculations.

The 7.5° corresponds to a frequency accuracy of

$$7.5^\circ = \tan^{-1}\left(\frac{\delta f}{f} 2Q_0\right)$$

for a δf of 117 Hz. In terms of a tuning sensitivity of approximately 10 kHz/mm this corresponds to 117Hz/10kHz/mm or 11.7 μm. This is well within the advertised accuracy of 2 μm of the servo.

III) Tuner Performance

Tuner sensitivity varies between 14.6 and 10 kHz/mm, while the required dynamic tuning range is 90 kHz $\pm$ 30 kHz of slow tuning to compensate for thermal detuning. This is easily met by less than 16mm of tuner travel, out of a possible 25mm.

The maximum tuning rate is given at the beginning of the acceleration cycle of gold and is 23kHz/sec.

A) Check maximum tuning rate: 23kHz/sec at 10kHz/mm = 2.3mm/sec. Pitch is 4mm/rev: (2.3mm/sec)/(4mm/rev)x2πrad/rev = 3.6rad/sec $\therefore$ Much less than the maximum motor speed at peak torque of 100 rad/sec and max. table speed of 160 mm/sec.

B) What is time required to reach maximum tuning rate (i.e., time between injection porch and maximum ramp)?

v=a*t, (3.6rad/sec)/(40180rad/sec^2) = .001sec ∴ Negligible compared to power supply slew rates.

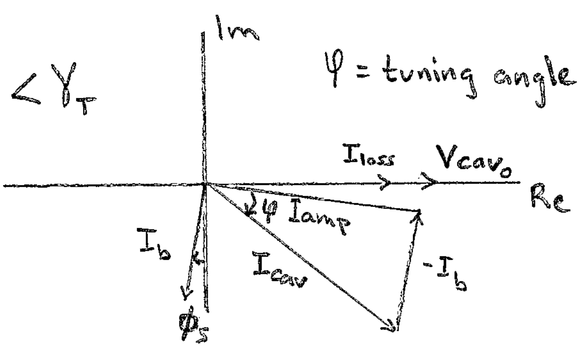
IV) Transition Crossing

At transition the tuner is moving at an initial velocity of (0.3kHz/sec)*(1/10kHz/mm)*(1/4mm/rev)*2π = 0.047rad/sec. We will see shortly that this is negligible compared to the result.

The detuning angle is given by

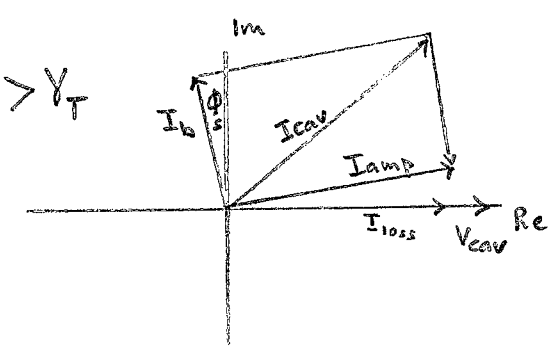
$$\Delta f_{rf} = \pm \frac{I_{fourier} \cos\phi_s}{2 * V_{cav}} \frac{R}{Q} f_{rf}$$

equals ± 660 Hz, positive below γ_T, negative above γ_T.



For zero beam loading the stable phase point ϕ_s is jumped in the low level electronics of the beam control system and the tuner does nothing. For full beam loading the tuner must swing through 2*Δf_{rf} or 2*660Hz = -1320 Hz (negative since going from +660 to -660 Hz). This corresponds to

$$\frac{1320Hz}{10kHz/mm} * \frac{1}{4mm/rev} * 2\pi rad/rev = 0.21 rad$$



We wish to know the minimum time required for the phase jump given the maximum speed of the table and the maximum acceleration rate. Given the maximum acceleration rate of 40180 rad/sec^2 and the initial velocity of 0.047rad/sec we can neglect the time required to reverse direction (1μsec). Solving for the time required to cover half the angle

$$\frac{0.21 rad}{2} = \frac{1}{2} a t^2$$

t = 2.3 msec. Checking that we do not exceed the maximum velocity v = at = 40,000rad/sec^3 * 2.3 msec = 92 rad/sec < 100 rad/sec maximum. Therefore minimum time required to switch phase at transition is 2*2.3msec = 4.6msec. W. Pirkl[2] has pointed out that the amplifier would see a substantially lower transient current at the anode if one "decompensates" for beam loading near transition, thus seeing an error of only Δf_{rf} rather than 2Δf_{rf}.

V) Overall loop response

The beam requires a phase accuracy of 0.15° of the rf voltage to avoid emmittance blowup. The fast rf feedback allows errors within the feedback loop to be reduced by a factor of 100, to 15°.

The initial tuning rate of 23kHz/sec for gold at the start of acceleration is the maximum rate encountered. The frequency shift corresponding to 15° is calculated as

$$\tan\Delta\psi = \frac{\Delta f}{f}2Q_0$$

Therefore Δf for 15 ° = 238 Hz. The time to accrue a 15 ° error is then 238Hz/23kHz/sec = 10msec. The outer tuning loop must therefore respond in less than 10msec, less than 5msec if we adhere to our 7.5° limit for a margin of safety. Since the outer loop is controlled via software this last requirement is near the pratical limit of the commercial controllers.

1) E. Onillion, private communication
2) D.P. Deng, "Emmitance Growth due to Phase Errors" rf Tech note RF-3.
3) W. Pirkl, unpublished informal note