AN AIR CORE QUADRUPOLE SYSTEM FOR FAST TUNE CONTROL IN CESR

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Abstract

The guide field magnets in CESR have a frequency response of 0.5 Hz. To allow fast control of betatron tunes we have installed a system of air core quadrupoles. We describe the air core quadrupoles and present results of tests of the system for tune control, hysteresis free beta function measurements, and tune feedback.

Introduction

The Cornell Electron Storage Ring, CESR, is an electron-positron collider. In CESR, counter-rotating particle beams travel in a roughly circular orbit inside a common vacuum chamber. The beams are guided by a strong focussing magnetic field produced by conventional iron dipole, quadrupole, and higher order pole magnets. These magnets have a finite hysteresis and a response frequency of about 0.5 Hz.

Precise tune control is essential to successful accelerator operation. We have built an air core quadrupole (ACQ) system, which is a set of quadrupole magnets without iron cores that is controlled independently of the CESR control system. The ACQ system is useful for inducing tune changes not possible with the iron quadrupoles for the following reasons: (1) the low inductance ACQ magnets have a response frequency of about 120 Hz; (2) the iron free magnets have no hysteresis; (3) the magnets can be used when the CESR control system is busy or temporarily non-functional.

One of the motivations to build this system was the prospect of tune feedback with both beam species in CESR. After filling CESR with electron and positron beams and before colliding, the magnetic guide fields are slowly changed via a linear interpolation to conditions optimized for colliding the beams. The speed of this transition is limited by tune slewing, which can result in loss of beams. Because the control system is busy during the transition, it is unable to respond to this problem. Feedback via the ACQs is a possible solution. We hope to test the technique soon.

Hardware Description

Two pairs of ACQs are installed symmetrically with respect to the two interaction regions. One pair is located in a region where the vertical betatron function is much greater than the horizontal, yielding preferential vertical focussing. The other pair is located conversely for horizontal focussing. The ACQs, weighing less than 20 pounds each, are mounted directly on the CESR vacuum chamber. Each ACQ has an associated current regulating power supply. From each power supply a shielded cable carrying control and readback signals runs to the central air core quad controller mounted in the CESR control room. A second cable from each power supply carries fault status signals to an interface crate connected to the CESR computer system.

The ACQs each have four coils wound of copper magnet wire, potted with epoxy. Since the magnetic field is shaped only by the coil windings and not by iron pole pieces, care was taken to wind the coils as identically as possible. The coils are supported in a frame of phenolic composite which is rigid, nonmagnetic, nonconductive and resistant to radiation damage. The frames have a clamshell hinge for ease in mounting. Magnet specifications are listed in Table 1. The measurements of field gradient and effective length were made with a Hall probe gaussmeter.

Table 1. Magnet Specifications

Physical length	51 cm
Physical aperture (radius)	6 cm
Magnetic length	45.3 cm
Magnetic aperture (radius)	4 cm
Wire guage	16 AWG
Turns per coil	214
Magnet resistance	11.8 Ohms
Magnet inductance	.093 Henry
Magnetic gradient per Amp	.0307 Tesla/meter

The power supplies take their power from the CESR magnet bus at 60-70 VDC. A pass regulator drops the voltage to 57 V to suppress bus voltage fluctuations. The controller floats the magnet between two push-pull transistor pairs to allow bipolar current flow through the magnet and uses negative feedback to provide linear current response. The supplies are protected against overheating and current draws above 2.5 A. Table 2 lists power supply specs. Note that at full 2.5 Amp current, the voltage drop across the 11.8 ohm magnet is only about 30 V; the extra 27 V of "headroom" allow the magnet to be driven to higher frequencies than its natural L/R rolloff frequency.

Table 2. Power Supply Specifications

Power source	60 to 70 VDC
Output into 12 ohm load	± 2.5 Amps
Control voltage gain	1.0 Amp/Volt
Readback voltage gain	2.0 Volt/Amp

The controller controls all four ACQs. Panel controls are as follows: (1) Disable/enable buttons for each power supply. (2) Manual tune knobs (±5 units) for horizontal and vertical betatron tune control. (3) External inputs (±5 V) for voltage control of the tunes. (4) Gain setting pots and switches used to give orthogonal tune control via manual or external controls. An explanation of the latter controls follows below. For each magnet a readback signal proportional to actual magnet current is provided.

Orthogonalization of Tune Control

The betatron frequency perturbed by a quadrupole responds according to the relations[1]

$$\Delta f = \frac{-1}{4\pi T}\,\beta k \Delta s \quad \text{with} \quad k = \frac{ec}{E_o} * \frac{\partial B}{\partial x}$$

where T is the revolution period (2.5 microseconds for CESR), β is the beta function, Δs is the effective length of the magnet, and Δf is the change in betatron oscillation frequency. k is the focussing strength of the magnet, where e is the electron charge, c is the speed of light, E_o is the particle energy (typically 5.3 GeV in CESR), and $\partial B/\partial x$ is the magnetic field gradient in the quadrupole magnet in

Tesla per meter. Because the horizontal beta function at the vertically focussing magnets is some fraction of the vertical beta function, the vertically focussing ACQs produce a parasitic Δf_h besides the desired Δf_v. The controller can be programmed to automatically compensate for this effect via the four gain controls.

The frequency changes Δf_v and Δf_h are given by

$$\begin{pmatrix}\Delta f_v\\ \Delta f_h\end{pmatrix} = C_0\begin{pmatrix}\beta_{1,v} & -\beta_{2,v}\\ -\beta_{1,h} & \beta_{2,h}\end{pmatrix}*\begin{pmatrix}I_v\\ I_h\end{pmatrix} = C_0\underline{B}*\begin{pmatrix}I_v\\ I_h\end{pmatrix}$$

where $\beta_{1,v}$ is the vertical beta function at the vertically focussing ACQ's (signified by the subscript 1), $\beta_{2,h}$ is the horizontal betatron function at the horizontally focussing ACQ's, I_v is the current in each of the vertically focussing ACQ's, etc. C_0 is a constant. The currents in the ACQs, I_v and I_h are given by

$$\begin{pmatrix}I_v\\ I_h\end{pmatrix} = C_2\begin{pmatrix}A_1 & A_2\\ A_3 & A_4\end{pmatrix}*\begin{pmatrix}C_v\\ C_h\end{pmatrix} = C_2\underline{A}*\begin{pmatrix}C_v\\ C_h\end{pmatrix}$$

where A_1 through A_4 are proportional to the gain settings for the controller and C_v and C_h are the commands (manual or external control). C_2 is a constant. Thus the frequency change produced is

$$\begin{pmatrix}\Delta f_v\\ \Delta f_h\end{pmatrix} = C_0C_2\underline{A}*\underline{B}*\begin{pmatrix}C_v\\ C_h\end{pmatrix}$$

If the matrix $\underline{A}$ is chosen to be the inverse of the matrix $\underline{B}$, frequency control will be orthogonal:

$$\begin{pmatrix}\Delta f_v\\ \Delta f_h\end{pmatrix} = C_0C_2\begin{pmatrix}C_v\\ C_h\end{pmatrix}$$

The product C_0C_2 and the matrix $\underline{A}$ are functions of the beta functions at the locations of the ACQs and must be calculated for each particular lattice of CESR quad strengths. It is easily seen that the range of orthogonal frequency control provided is the same in both planes. A different set of gain settings (produced by making the product $\underline{A}*\underline{B}$ diagonal but with unequal diagonal elements) can also be used to give greater frequency range in a prefferred plane. In a typical lattice the range of orthogonal control is *3 to *4 kHz.

System Frequency Response

To remove noise picked up over the 1000 ft. control and readback cables connecting each power supply to the controller, double pole low pass filters (pole at 920 Hz) are placed at the receiving end of each line: one at the control signal input to the power supply, and one at the readback signal input to the controller. All four poles should be observed in the readback signal's transfer function; only two of the poles affect the actual ACQ current. Each ACQ has an intrinsic low pass response characterized by a pole at 20 Hz due to L/R. As already mentioned, the incorporation of the magnet inside the feedback loop and the voltage "headroom" available raise the effective rolloff frequency of the magnet. We examined the system's response regarding all of the above effects.

The magnetic field of the ACQs is attenuated by the CESR vacuum chamber. The thickness d and conductivity g of the vacuum chamber walls determine the attenuation of the field as a function of frequency. The field drops to one half of its strength at a frequency

$$f = \frac{2\log(.5)}{2\pi\, d^2 g\, \mu}^{1/2}$$

where μ is the magnetic permeability ($4\pi*10^{-7}$ for non-magnetic materials). For the two different vacuum chambers at the horizontally and vertically focussing ACQs, the calculated frequencies for one half strength response are approximately 85 Hz and 7.2 kHz respectively. These poles should appear in the measured transfer functions.

Experimental Evaluation

A. System Frequency Response

The observed current readback transfer function shows a pole at approximately 120 Hz (the magnet's pole) and several poles at about 900 Hz. A calculation placing a pole at 120 Hz (based on the observed pole) and four poles at 920 Hz (the calculated frequency of the filter poles) shows good agreement with the observed transfer function.

Next the tune tracker output, proportional to the betatron frequency change, was examined. As expected, the two poles at 920 Hz and the pole at 120 Hz appear; for the horizontally focussing ACQ's an extra pole at about 150 Hz due to the vacuum chamber effect is seen, giving a slope of 40 dB per decade initially. The observed and calculated responses (assuming these poles) are shown in Fig. 1. The 7.2 kHz pole in the vertical tune response (Fig. 2) occurs at too low gain to be observed. The tune tracker response is so fast that it contributes no measurable effect.

Fig. 1: Horizontal Tune Transfer Function

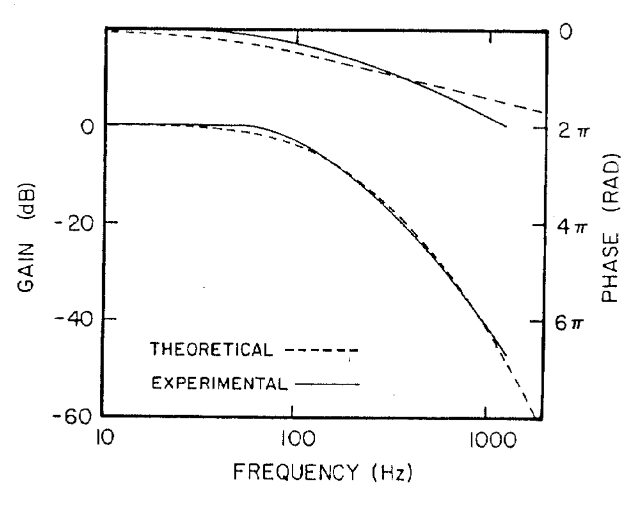
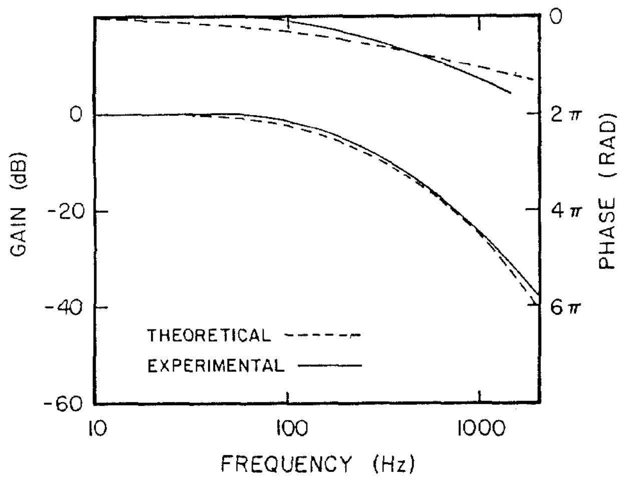


Fig. 2: Vertical Tune Transfer Function



B. Orthogonal Operation

The betatron frequency changes due to each pair of ACQs were measured. The theoretical frequency changes based upon the theoretical values of the beta functions and the measured magnetic gradient of the ACQs (Table 1) are compared with the observed frequency changes in Table 3.

Table 3. Frequency Changes

	Measured Δf	Theoretical Δf	Error (%)
H ACQS	Δf_v -1.34	Δf_v -1.19	13
	Δf_h +8.05	Δf_h +5.88	37
V ACQs	Δf_v +12.3	Δf_v +9.96	23
	Δf_h -3.70	Δf_h -2.79	33

The observed Δf's are 13 to 37% higher than expected, implying that the ACQs may be stronger than indicated by the bench measurements. Note however that since the errors are so different, a large portion of the error must be in the theoretical values, since observed Δf's for one set of ACQs must be in the ratio of the actual beta functions regardless of ACQ strength. The ACQs are potentially the most effective means of measuring the betatron functions; theoretical values of the beta functions are often in error by 10% or more. For this reason, we have not yet verified rigorously the predicted focussing strength of the ACQs.

The experimental data were used to calculate the controller gains needed for orthogonal operation. Using these values, the tunes were observed to be orthogonal to within 1% over a range of ± 4 kHz. The errors seen are on the same level as the uncertainty in tune tracker readout.

C. Tune Feedback

For a negative feedback loop to be stable (with a phase safety margin of 45 degrees), the loop gain must be less than one at the frequency where the phase shift approaches 135 degrees. This means that the gain must be less than one at the frequency of the second pole.

The transfer function of the horizontal betatron frequency driven by the horizontally focussing ACQs showed one pole at about 120 Hz for the magnet's response and one at 150 Hz for the beam pipe's attenuation. To achieve a stable feedback transfer function we placed an active amplifier with a zero at the lowest pole on the output of the tune tracker, leaving one dominant pole at about 150 Hz, and two poles at 900 Hz. The controller gains were set at maximum, with polarity to provide negative feedback; the vertically focussing ACQs were turned off, and the active amplifier output was fed into the controller input to close the loop. The DC gain of the complete loop was set to about 6. The main quadrupole control which normally determines the betatron frequency was varied over a range of 500 arbitrary units with no feedback, and then with feedback . Without feedback, the tune change was 7.0 kHz; with feedback the change was 1.3 kHz, for a ratio of 5.4:1, consistent with the gain of about 6. The experiment was repeated for the vertical tune with a net loop gain of approximately 9; the results were similar, with a tune change ratio of 7.4:1. Feedback response was linear.

This was a temporary mockup serving only to verify that feedback is feasible; a more sophisticated configuration would increase the DC gain by moving the first pole to a lower frequency, with no loss of higher frequency response. By operating in the orthogonal mode, simultaneous feedback on both tunes is possible.

Conclusions

The linear behavior of the ACQs has been verified, and the feasibility of tune feedback has been demonstrated. Orthogonal tune control has been demonstrated. Due to uncertainty in the theoretical beta functions at the ACQ locations, the accuracy of bench measurements of the magnet gradient (quoted in Table 1) has not been verified rigorously. Future work using the ACQ system will include tune feedback with two beam species, and will exploit the fast response to make quick excursions into and across areas of the tune plane where beam lifetimes are poor.

Acknowledgements

The authors wish to thank the CESR operations staff and technical support staff for their contributions in the conception, construction, implementation and testing of the ACQ system. This work was supported by the NSF.

References

[1] M. Sands, The Physics of Electron Storage Rings, Stanford Linear Accelerator Center Report, SLAC-121, 1970.