

# Open Loop Compensation for the Eddy Current Effect in the APS Storage Ring Vacuum Chamber\*

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## Abstract

In the third generation synchrotron light sources, closed orbit stabilization against external vibrations is critical to ensure low emittance and high brightness. The Advanced Photon Source (APS) will use a large number (678) of correction magnets to create local bumps and to achieve global orbit stabilization. In this paper, we will present the result of the effort to counter the effect due to the finite inductance of the magnet and the eddy current in the 1/2"-thick aluminum storage ring vacuum chamber. The amplitude attenuation and the phase shift of the correction magnet field inside the APS storage ring vacuum chamber were measured. A circuit to compensate for this effect was then inserted between the signal source and the magnet power supply. The amplitude was restored with an error of less than 20% of the source signal amplitude and the phase shift was reduced from 80° to 12° at 10 Hz. Incorporation of this circuit in the closed loop feedback scheme and the resulting beneficial effect in the closed orbit stabilization will be discussed.

## I. INTRODUCTION

A number of correction dipole magnets will be installed around the APS storage ring to stabilize the beam against the low frequency vibration below 25 Hz from various sources. The correction magnet system consists of 80 main dipole trim coils, 280 sextupole dipole coils, 240 vertical field dipole magnets for horizontal corrections and 78 vertical/horizontal field magnets for horizontal and vertical corrections. A detailed description of the design specification parameters for these magnets can be found in Ref. [1]. The displacement of the quadrupole magnets due to vibration has the most significant effect on the stability of the positron closed orbit in the storage ring. A small displacement of the quadrupole magnet leads to a large distortion of the closed orbit, and hence, the growth of the emittance.

This article describes the measurement of the eddy current effect on the externally applied correction magnet field to counter the low frequency (< 20 Hz) vibration. The correction magnets are controlled individually through the feedback loop comprising the beam position monitoring (BPM) system. We will concentrate on compensation for the eddy current effect using an open loop circuit. Incorporation of this circuit in the closed loop feedback scheme and the beneficial effect in the closed orbit will be also discussed.

## II. MEASUREMENT SETUP

For the measurement of the amplitude attenuation and the phase shift, sine waves of various frequencies up to 25 Hz were used. Square waves and triangular waves were also used to measure the rise time of the magnetic field inside the vacuum chamber or to demonstrate the performance of the compensation circuit inserted between the function generator and the power supply.

Figure 1 shows the measurement setup, with a section of the APS storage ring vacuum chamber in the magnet bore. Since the bore is too small for the entire vacuum chamber to fit in, the antechamber was cut away, leaving only the positron beam chamber and the photon beam channel. This will have negligible effect on the measurement because of the large aspect ratio of the photon beam channel. The magnet was one of the dipole magnets used in the electron cooling ring experiment at Fermilab[2].

With the inductance  $L = 10$  mH and the coil resistance  $R_c = 25$  m $\Omega$ , the time constant of the magnet  $\tau_c$  is equal to  $L/R_c = 400$  ms. In order to reduce the time constant, a water-cooled stainless steel resistor of  $R = 0.2$   $\Omega$  was connected in series to the magnet, as shown in Fig. 2. This reduced the time constant  $\tau$  to 44 ms.

The unperturbed field is measured with a current transducer ( $V_c$ ), while the field inside the vacuum chamber is measured simultaneously with a Hall probe ( $V_g$ ) and a gaussmeter (G).

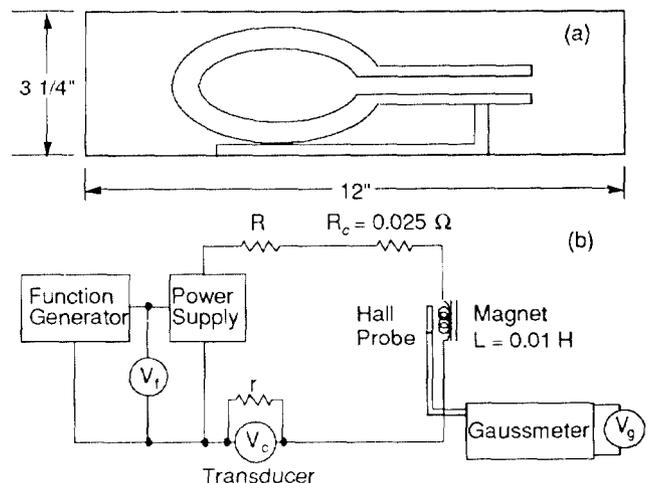


Fig. 1: (a) A section of the vacuum chamber cut short to fit into the magnet bore. (b) Electrical connection.

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The field attenuation and the phase shift can then be calculated by comparing  $V_c$  and  $V_g$ .

### III. COMPENSATION CIRCUIT

In order to restore the magnetic field inside the vacuum chamber to the same shape as the driving signal, it is necessary to amplify the attenuated frequency components and to advance their phases accordingly. Consider the following relation.

$$\begin{aligned} V_c(t) &= \int d\omega V_c(\omega) e^{-i\omega t}, \\ V_g(t) &= \int d\omega a(\omega) e^{i\Delta\phi(\omega)} V_c(\omega) e^{-i\omega t}. \end{aligned} \quad (1)$$

Here,  $V_c(t)$  is the unperturbed field and  $V_g(t)$  is the field inside the vacuum chamber, and  $V_c(\omega)$  and  $V_g(\omega)$  are the Fourier transforms. Let  $a_v$  and  $a_m$  be the attenuation factors due to the vacuum chamber and the magnet, respectively, and let  $\Delta\phi_v$  and  $\Delta\phi_m$  be the phase shifts. Then the overall attenuation factor  $a$  and the overall phase shift  $\Delta\phi$  will be

$$a = a_v a_m \quad \text{and} \quad \Delta\phi = \Delta\phi_v + \Delta\phi_m. \quad (2)$$

If  $\Delta\phi(\omega)$  is close to  $90^\circ$  and if  $a(\omega)$  behaves like  $\omega^{-1}$  within the frequency range where  $|V_c(\omega)|$  is appreciably large, then  $V_g(t)$  is simply the time integration of  $V_c(t)$  except for a real multiplication factor. In this case, the compensation can be achieved by feeding the differentiation of the driving signal to the magnet. Let  $V_i(t)$  be the source signal and let  $V_i(\omega)$  be its Fourier transform. The ideal compensation circuit would then modify the source signal such that

$$V_c(\omega) = \frac{1}{a(\omega)} e^{-i\Delta\phi(\omega)} V_i(\omega). \quad (3)$$

This can be partially achieved by using a simple circuit element shown in Fig. 2. A simple argument shows that this circuit always gives attenuation which decreases monotonically with frequency and frequency dependent phase advance at all frequencies. The maximum phase advance achievable with this circuit is less than  $90^\circ$  and depends on the ratio  $R_1/R_2$ . It occurs at some frequency  $\omega$  satisfying  $R_1 < 1/\omega C < R_2$ . Assuming harmonic time dependence  $e^{-i\omega t}$  and putting  $r = R_1/R_2$  and  $\tau = R_1 C$ , the exact relation between  $V_i$  and  $V_f$  is

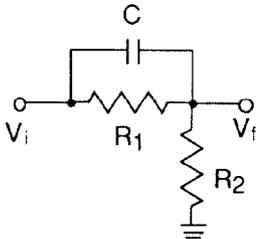


Fig. 2: An element of the open loop compensation circuit.

$$\frac{V_f}{V_i} = a'(\omega) e^{i\Delta\phi'(\omega)} \quad (4)$$

where

$$\begin{aligned} a'(\omega) &= \frac{[\{1 + r + (\omega\tau)^2\}^2 + (r\omega\tau)^2]^{1/2}}{(1+r)^2 + (\omega\tau)^2}, \\ \Delta\phi'(\omega) &= -\tan^{-1} \left( \frac{r\omega\tau}{1 + r + (\omega\tau)^2} \right). \end{aligned} \quad (5)$$

This circuit has two disadvantages. One is that the low frequency components are attenuated significantly due to large  $r$ . Secondly, it does not have the isolation property needed to shift the phase by more than  $90^\circ$ . These problems can be solved easily by adding an op-amp at the output terminal. Two such circuits were used in combination to compensate for the magnet inductance and the eddy current effect. The parameters  $r$  and  $\tau$  were chosen such that the low frequency behavior of  $\Delta\phi'$  follows the measured values as closely as possible up to 10 Hz while maintaining  $aa' \approx 1$ . If we let  $a'_v$ ,  $\Delta\phi'_v$ ,  $a'_m$  and  $\Delta\phi'_m$  be the amplification and the phase correction by the first and the second stages, then the overall compensation will be represented by

$$a' = a'_v a'_m \quad \text{and} \quad \Delta\phi' = \Delta\phi'_v + \Delta\phi'_m. \quad (6)$$

From Eqs. (2) and (6), the attenuation and phase shift after compensation will be given by

$$a_c = aa' \quad \text{and} \quad \Delta\phi_c = \Delta\phi + \Delta\phi'. \quad (7)$$

### IV. MEASUREMENTS AND RESULTS

The current transducer and the Hall probe used for the field measurement were first checked for linearity in their response to DC and AC fields. For DC linearity check, the field was increased up to  $G = 1,200$  gauss and  $V_c/G$  and  $V_g/G$  were measured. The results were:

$$\begin{aligned} V_c/G &= 0.608 \pm 0.010 \text{ (mV/gauss)}, \\ V_g/G &= 0.382 \pm 0.004 \text{ (mV/gauss)}. \end{aligned} \quad (8)$$

These numbers are the calibration constants for field measurements. For AC,  $V_c/V_g$  was measured for frequencies up to 25 Hz. The DC bias level was set at 1,200 G and the power supply was modulated at various frequencies. The AC field amplitude was set at approximately 25% of the DC bias level, i. e., 300 G. No attenuation or phase shift in the Hall probe response was observed as a function of the driving current in the magnet. After calibration using Eq. (1), we found:

$$V_c/V_g = 0.973 \pm 0.010. \quad (9)$$

After checking the linearity in the Hall probe response, it was placed at the center of the positron beam chamber.

Two separate measurements were made to determine  $a_v$ ,  $\Delta\phi_v$  and  $a_m$ ,  $\Delta\phi_m$ . To measure  $a_v$  and  $\Delta\phi_v$ , the current in the magnet, which was converted to voltage  $V_c$  by the transducer, was used as reference and the Hall probe signal  $V_g$  was compared with  $V_c$ . Similarly, to measure  $a_m$  and  $\Delta\phi_m$ , the driving signal  $V_f$  from the function generator was used as reference and the signal  $V_c$  was compared against  $V_g$ . Figure 2 shows the results of these measurements, (a) for the attenuation factors and (b) for the phase shifts.

Figure 3 summarizes the measurement results. It shows that compensation for amplitude attenuation is very good up to 20 Hz. The remaining phase shift is  $12^\circ$  at 10 Hz and  $35^\circ$  at 25 Hz. This deviation comes mostly from the vacuum chamber. This result is obvious since the eddy current effect can shift the phase by more than  $90^\circ$ , while the compensation circuit works only up to  $90^\circ$ . However, unless the source signal, e. g., the vibrational motion that needs to be corrected, has a broad-band spectrum reaching beyond 10 Hz, these deviations will not pose a serious problem.

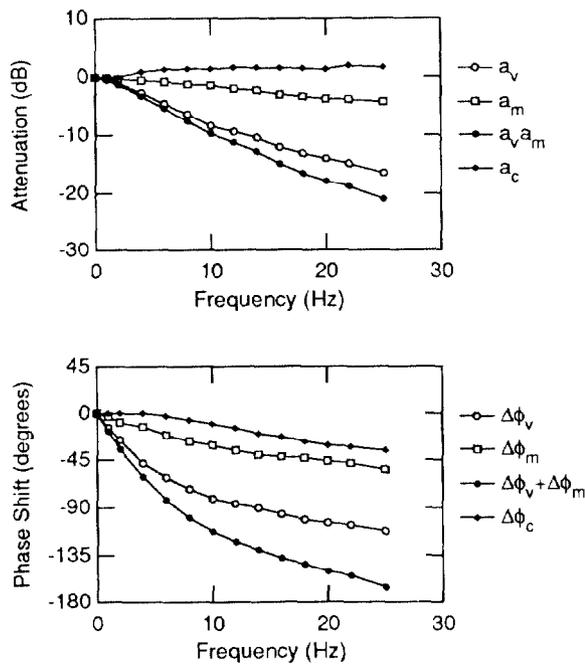


Fig. 3: Amplitude attenuation and phase shift due to the eddy current effect.

## V. CLOSED LOOP COMPENSATION

The present work considered only the open-loop compensation without any feedback from the resultant magnetic field inside the vacuum chamber. For better compensation for the eddy current effect in a broader frequency range, a local closed loop feedback scheme[3-4] must be used. In the APS storage ring, the local loop will employ photon beam position monitors to detect the position and the angle of the beam. Let  $A$  be the open loop gain. Then, with the loop closed, the overall compensation will be given by

$$\frac{V_f}{V_i} = \frac{aa'A}{1 + aa'A} \quad (10)$$

From Eq. (10), we find that a large gain ( $|aa'A| \gg 1$ ) is needed for the loop to work. However, by Nyquist's theorem, this will cause instability or amplitude growth if the phase delay due to the eddy current effect (a) increases to near  $180^\circ$ , and hence, decrease of the bandwidth of stable operation. This problem can be alleviated by incorporating the open loop circuit (a') in the loop, as shown in Fig. 4. Measurements similar to those described in this paper have been made using this scheme and near perfect compensation for the eddy current effect was achieved ( $|a_c| \approx 0.95$  and  $\Delta\phi_c \approx -7^\circ$  at 25 Hz). The results will be published separately in the near future.

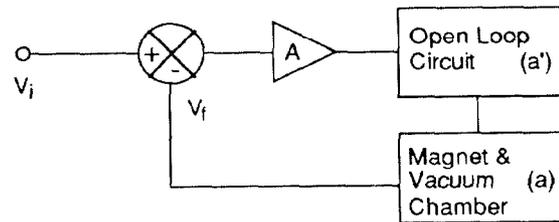


Fig. 4: Incorporation of the open loop circuit in the closed loop feedback.

## V. SUMMARY

The measurements performed on the field attenuation and the phase shift due to the eddy current in the APS storage ring vacuum chamber were described. The finite inductance of the magnet adds to this effect. As a solution to correct this problem, a simple circuit was designed and inserted between the signal source and the magnet power supply. The compensation was almost complete below 10 Hz, and between 10 and 20 Hz, more than 85% of the phase shift was corrected. Incorporating the open loop circuit in the closed loop feedback shows much improved compensation.

## VI. REFERENCES

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