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A NEW METHOD OF UNDULATOR PHASE TUNING WITH MECHANICAL SHIMMING*

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Abstract

We developed a new method for tuning the undulator phase errors by shimming the undulator gap profile mechanically. First, the phase errors of a device are calculated based on the initial field measurement. Then the desired field strength modulation along the device length is derived from the phase errors. Finally, the gap profile is mechanically shimmed to produce the desire field strength modulation. The method has been successfully applied to the tuning of many new and reused APS Upgrade (APS-U) hybrid permanent magnet undulators. The method is especially effective for tuning the legacy undulators with large phase errors. For instance, an old 33-mm-period undulator with a 23° initial RMS phase error largely due to radiation damage has been tuned to better than 3°.

INTRODUCTION

One of the main sources of undulator phase error is the field strength variation along the length of the device. There are very tight requirements on the mechanical precision of the magnets and poles. However, due to the existence of imperfections in the magnets and poles, a mechanically perfect gap cannot guarantee an optimal phase error distribution.

On the other hand, a small perturbation has a predictable effect on the field, and the resultant phase error change is also predictable. Therefore, adjusting the gap opening has long been adopted in various undulator projects to tune the phase error [1]. For example, some of the hybrid permanent magnet undulators (HPMUs) have specially designed mounting structures like differential screws [2] for easy phase tuning by shimming the gap. The APS-U is going to reuse legacy HPMUs that were not designed to have a similar structure [3], but gap shimming for these devices is very time consuming. Therefore, a method that can tune the phase error by more efficiently shimming the gap is demanded. In this report, we present the newly developed method for this purpose.

CALCULATION PROCEDURE

For an ideal undulator with no field error, the phase advance between two consecutive poles is π at the first harmonic radiation wavelength λ_L,

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2}), \tag{1}$$

where λ_u is the period length. Assume the gap is non-uniform, and the gap at the i-th pole is g_i, the mean gap is $\bar{g}$, and

$$\Delta g_i = g_i - \bar{g}.$$

The deformed gap causes the field to change from the nominal value by [4]

$$\Delta B_i = -\pi\frac{\Delta g_i}{\lambda_u}\bar{B}.$$

Likewise, the undulator deflection parameter at the i-th pole is given by

$$K_i = \bar{K} - \pi\frac{\Delta g_i}{\lambda_u}\bar{K}, \tag{2}$$

where $\bar{K} = 93.4\bar{B}\lambda_u$ is the undulator deflection parameter of the nominal field strength.

The radiation wavelength of the on-axis first harmonic $\bar{\lambda}$ from $\bar{K}$ is used as a reference in the phase error calculation. We denote the phase error change at the i-th pole as $\delta\phi_i$:

$$\delta\phi_i \equiv \phi_{i+1/2} - \phi_{i-1/2} = \pi\left(\frac{\lambda_i}{\bar{\lambda}} - 1\right),$$

where $\phi_{i\pm1/2}$ denotes the phase error at the center of the two magnets that touch the i-th pole, and λ_i is the radiation wavelength calculated from K_i. By substituting Eqs. (2) and (1) into the above equation and neglecting the higher-order terms, we have

$$\delta\phi_i = -\pi^2\frac{2\bar{K}^2}{2+\bar{K}^2}\frac{\Delta g_i}{\lambda_u}. \tag{3}$$

Equation (3) links the phase error and the gap variation. With the $\bar{K}$ of a gap and λ_u known, one can get a gap-shaped curve that approximates the phase error measured at that gap. By shimming the gap to that shape, the phase error will be minimized.

IMPLEMENTATION EXAMPLE

A total number of 23 legacy HPMU devices from the current APS will be reused for the APS-U project. These devices were constructed and tuned about 20 years ago and have been in operation since that time. The specification for the RMS phase error of these devices is less than 3° for all operating gaps.

Due to the demagnetization of permanent magnets, these legacy devices suffer from low field quality, especially large phase errors. Among the nine tuned legacy devices, U33#19 has the largest initial phase error of 23°. This device has a period length of 33 mm, an operation gap range of 10 to 30 mm, and a total of 146 poles. The field close to the z- end of this device was seriously weakened as shown in Fig. 1,

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probably due to the radiation damage. We use this device to demonstrate the workflow we used to correct the phase error by gap shimming.

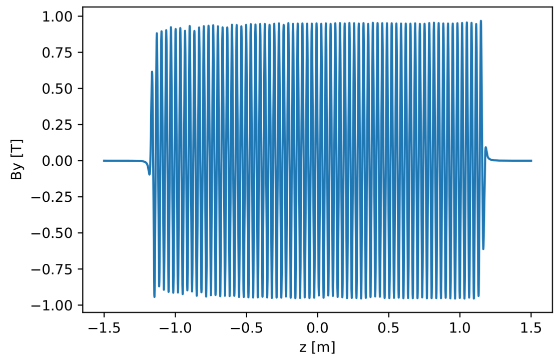

Figure 1: The field profile of U33#19 at a gap opening of 10 mm. Field attenuation is obvious at the z- end.

Phase Error Data Reduction

Undulator trajectory error contributes to phase error, so the trajectory was corrected before gap shimming began. Once the trajectory was straightened, directly applying the differential operator to the phase error still did not produce meaningful $\delta\phi_i$ because the phase error was still noisy. Hence, we used smoothing methods to find the trend lines of the phase error and then used the trend lines. One method we tested was based on a Fourier transform (FFT), which transforms the phase error data into the frequency domain, keeps the lower-order components, and omits the higher-order components. Another method we used was the moving average. The two methods are shown in Fig. 2; both work well when the proper parameters are chosen. For U33#19, the moving average method was chosen.

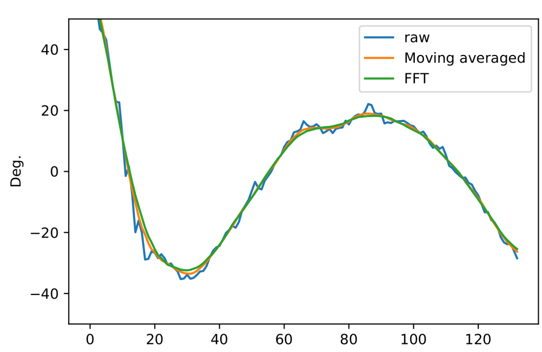

Figure 2: Smoothing the phase error of U33#19. The first nine orders of the Fourier series were kept for the FFT method. For the moving average method, the sliding window covers ±7 poles.

Virtual Gap Shape

After the trend lines of the phase error were obtained, we derived the desired gap deformation Δg_i by using Eq. (3). Usually the linear component in the desired gap deformation should be removed since the linear component could be produced by the taper mechanism of an HPMU.

Different gaps give different virtual gap shapes, as shown in Fig. 3. This is reasonable because the real sources of phase errors have different gap dependencies. In our cases, we derived the desired gap deformation for compensating phase errors mostly at the minimum operating gaps.

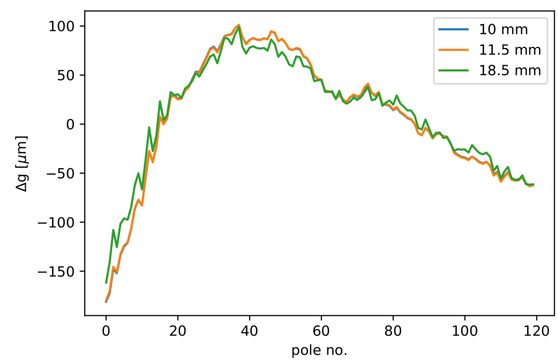

Figure 3: Desired gap deformation for compensating phase errors at different gaps. Poles close to the ends are skipped.

Mechanical Shimming

Figure 4 shows the mechanical structure for holding the magnet arrays of APS-U legacy HPMU devices. The magnets and poles are mounted on an aluminum keeper, and a movable strongback of non-magnetic material is connected to the undulator steel framework through ball screws. The keeper is attached to the strongback by bolts, and brass shims can be placed between the keeper and the strongback at these bolting locations. Given that the strongback is much more rigid than the keeper, only the keeper will deform when increasing or decreasing the thickness of the shim. The gap between the top and bottom magnet arrays will also change.

The minimum thickness of the brass shim is 12 μm, which defines the resolution of the gap shimming.

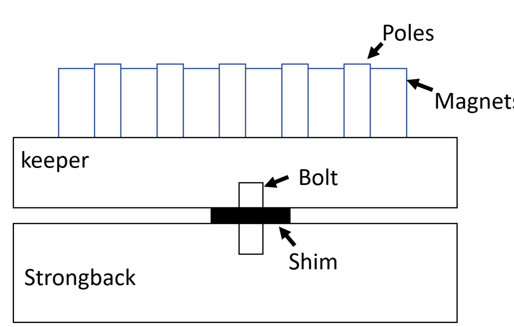

Figure 4: Fixture for the magnet array.

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Phase Correction Results

The result after the gap shimming is shown in Fig. 5. We can see that the systematic components have been removed. The RMS phase error at the 10-mm gap was reduced from 22.7° to 2.94° after two rounds of gap shimming were performed, and the RMS phase errors across the operation gap range are all better than 3°. This is a notable improvement given that only a small amount of tuning effort and time was needed.

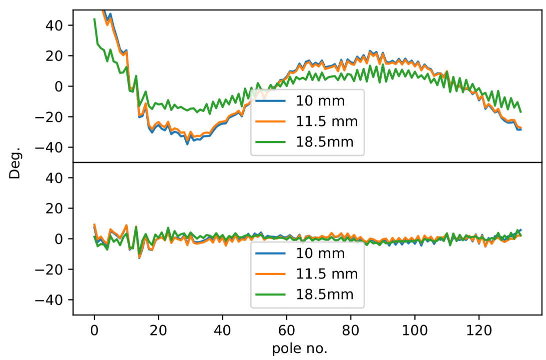

Figure 5: Phase errors of U33#19 at different gaps before (top) and after (bottom) the gap was mechanically shimmed. The RMS phase error at the 10-mm gap was reduced from 22.7° to 2.94°.

The gap relative deformation due to gap mechanical shimming was measured by a Capacitec sensor. The gap deformation can also be derived by applying Eq. (3) to the phase error before and after gap shimming. Deformation data from these two methods are compared in Fig. 6. The agreement among these data shows that the phase-error-based method we used in this report can represent the relative gap deformation at a reasonable precision, regardless of the gap from which the phase error data were obtained.

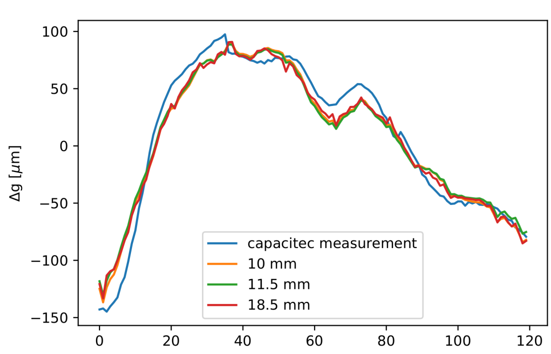

Figure 6: Gap deformation from Capacitec measurement and phase error measured at different gaps.

CONCLUSIONS

In this report, we present a new and efficient method for phase error correction by mechanically shimming the gap with the guidance of phase errors. This approach was successfully applied to all nine re-tuned legacy HPMU devices and one newly constructed HPMU device for the APS-U project.

The accurate calculation of the desired gap deformation reduces the number of iterations of gap shimming needed and ultimately the amount of time and effort spent tuning the undulators. Therefore, this method is useful for projects with a large number of HPMU devices, especially for projects that need to tune HPMU devices of poor quality. This method can be used in the phase error correction of the superconducting undulators.

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