HE-SXU Midplane Position Errors And Corrections

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Abstract

The midplane position of the SXR undulators changes with gap. For the high energy upgrade project, encoders are being added to correct the midplane position. Initial tests showed that significant errors in the midplane position remained after correction with the new encoders. This note discusses the source of the errors and gives a fix for the problem.

1 Introduction[1]

Midplane encoders were installed on the HE-SXR undulators in order to correct the magnetic axis position. The magnetic axis position is important for two reasons. In the MMF the measurements must be done on the magnetic axis where the change in K with Y-position is very small. By measuring on the magnetic axis, we minimize the effect of alignment errors on the K value. The measurement probes move on a fixed line. The undulator magnetic axis must remain on that line at all gaps for accurate K measurements. When the undulator is in operation, the magnetic axis must remain on the beam path so the K value the beam sees is given by the calibration done in the MMF. The midplane encoders were installed to help solve both midplane alignment problems.

It was found in the MMF that the correction using the new encoders still produced errors in the midplane position. The correction reduced the midplane position error, but a sizeable residual error remained. This note attempts to explain the source of the error and gives a remedy.

2 Midplane Behavior Without Correction

The control system sets the SXR undulator gaps using two sets of encoders. The upper jaw is set to half the desired gap value using absolute encoders on the motors. The lower jaw is set using the gap encoders to get the desired gap.

This scheme does not control the undulator midplane position. The midplane position is given by the position of the upper jaw poles minus half the gap. In the control system the upper jaw motor encoders are set correctly to nominally move the poles to half the

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gap, and the gap is set correctly by the gap encoders to adjust the lower jaw motors, but compliance of the drivetrain between the upper jaw motors and the upper jaw poles is not accounted for. The lower jaw exerts magnetic forces on the upper jaw and pulls the upper jaw down as the gap is closed. Even though the motor position is correct, compliance in the drivetrain allows the upper jaw to move down.

The measured motion of the midplane is plotted in Figure 1 using touch probe measurements on HE-SXU-000. The upper and lower magnet pole positions were determined by the touch probe and the midplane position was calculated as the mean of the upper and lower pole vertical positions. Using the 33 mm gap midplane position as a reference, the midplane goes down by 110 microns as the gap is closed to 7.5 mm. This large shift in the midplane would affect the measured K value of the undulator if it were not corrected.

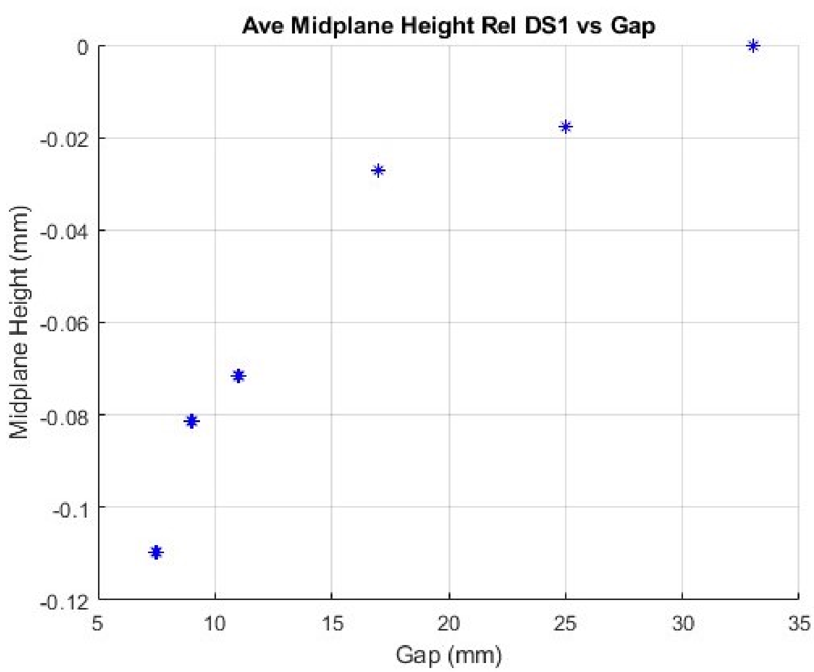

Figure 1: Uncorrected midplane position as a function of gap for HE-SXU-000.

3 Midplane Encoders

The midplane position must be corrected so that our fixed height probes always measure on the magnetic axis and so that in operation the beam goes down the magnetic axis. In order to implement a midplane correction, encoders are being added to the undulators. The encoders measure the position of the upper jaw relative to the fixed frame of the undulator.

The midplane correction is envisioned to work as shown in Figure 2. The midplane

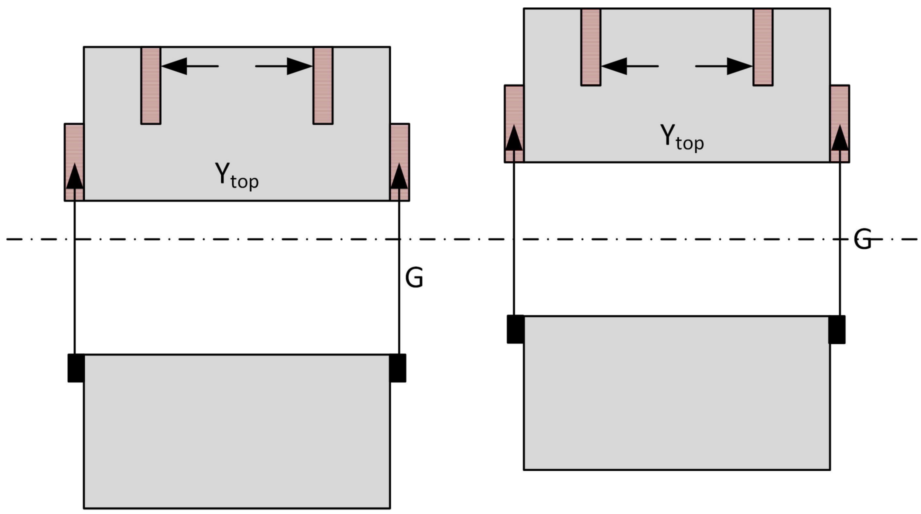

Figure 2: Midplane encoders measure the position of the top jaw.

encoders (toward the middle of the upper jaw in the figure) measure the position of the upper jaw relative to the fixed undulator frame. They are calibrated at a reference gap with the midplane aligned to the measurement axis to give the position of the top of the gap, Y_{top}. The gap encoders give the gap G. The position of the midplane is given by

$$Y_{mid} = Y_{top} - \frac{G}{2} \tag{1}$$

Since the midplane is on the measurement axis at the reference gap, which we define as $Y = 0$, we have $Y_{mid} = 0$ and $Y_{top} = G/2$ at the reference gap. When the gap is set to any other value, the midplane and gap encoders are read and Y_{mid} is calculated. If Y_{mid} is not zero, both the upper and lower jaws are moved together until $Y_{mid} = 0$. In this way all the measurements ideally are done on the magnetic axis.

Figure 3 shows the midplane encoders mounted on HE-SXU-000. Figure 4 is a close-up view of a midplane encoder showing the scale mounted on a backing plate. Figure 5 shows that the midplane encoders are mounted at about the same height as the upper jaw support points.

Figure 3: Midplane encoders are mounted inside the blue vertical supports near the top of the undulator.

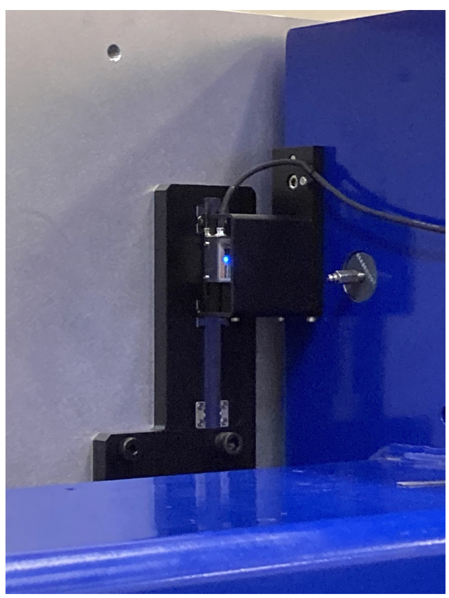

Figure 4: Midplane encoder showing the scale mounted on a backing plate attached to the upper jaw and the read head mounted on the undulator frame.

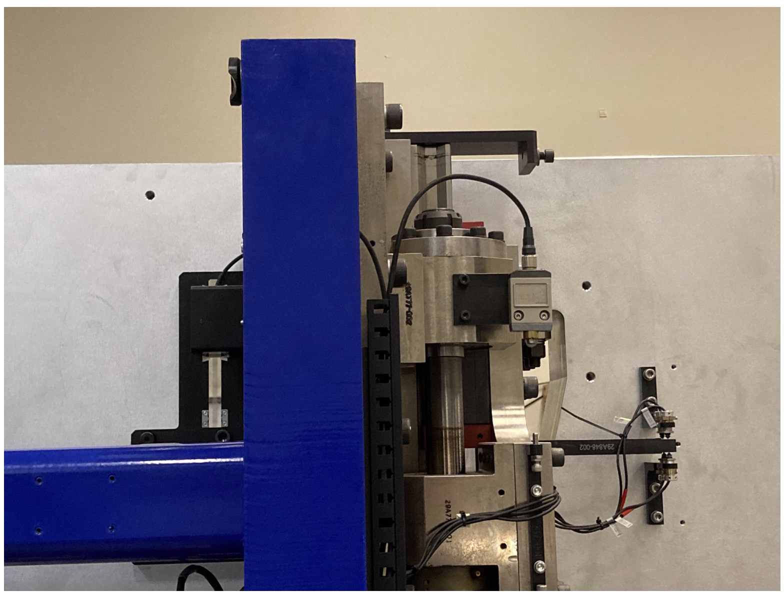

Figure 5: The midplane encoders are mounted at about the same height as the upper jaw support points.

4 Midplane Correction Performance

A set of measurements was done in order to test the performance of the midplane encoders. The undulator was set to a given gap. The midplane encoders were read and both the upper and lower jaws were moved so that the gap stayed constant and the midplane encoders read half the gap height. This should keep the midplane height constant at the probe height, $Y = 0$. After the gap and midplane were set, Hall probe scans were made and the K value of the undulator was determined at different Y-positions. The Y-position where K is minimum gives the Y-position of the magnetic axis of the undulator. Figure 6 shows data from a typical set of scans for 33 mm gap. Third order fits to the measurements were used

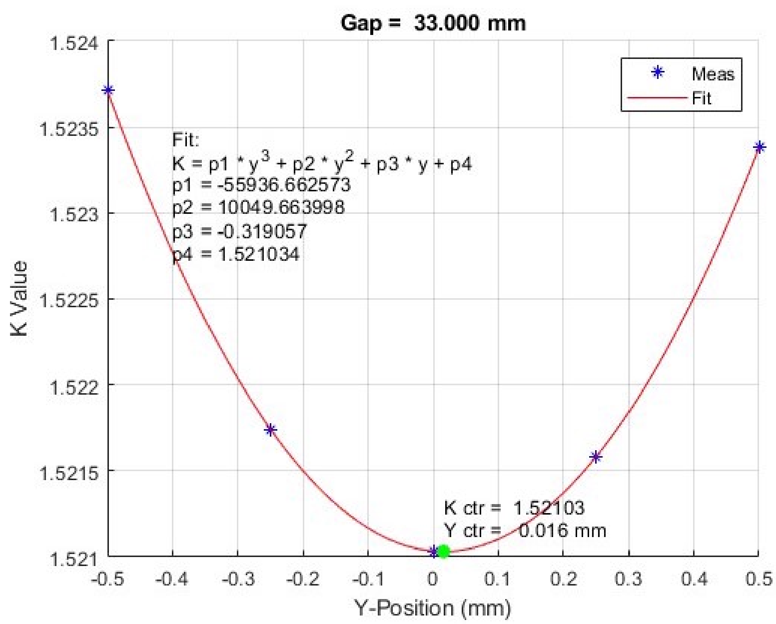

Figure 6: K vs Y for 33 mm gap.

to find the minimum K value (magnetic center) since second order fits had large residuals at small gap. Figure 7 shows the fit results for 7.2 mm gap and all points touch the curve with the third order fit.

When the Y-positions of the magnetic center are plotted as a function of gap, the resulting plot is shown in Figure 8. The magnetic axis position shifts downward by about 40 microns as the gap is closed from 33 mm to 7.2 mm.

If one chooses the magnetic axis position at 33 mm as a reference, the plot shown in Figure 9 results. In this plot the change in magnetic axis position by about 40 microns is clearly visible.

For these plots, after the gap was set, the upper and lower undulator jaws were moved together until the midplane encoders read half the gap value. This was expected to center the gap at a fixed height on the probe measurement axis. In this case, why does the magnetic axis position change with gap instead of staying fixed at $Y = 0$?

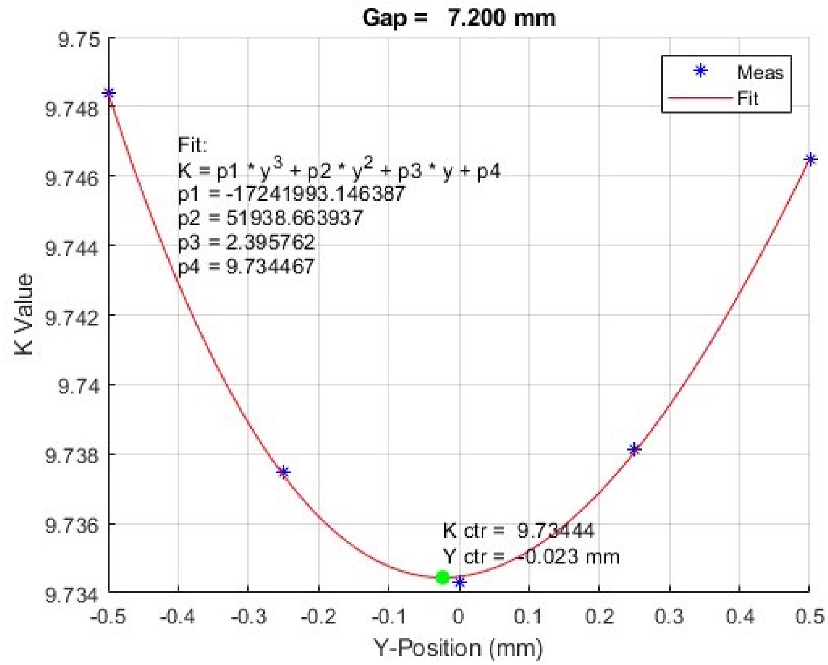

Figure 7: K vs Y for 7.2 mm gap.

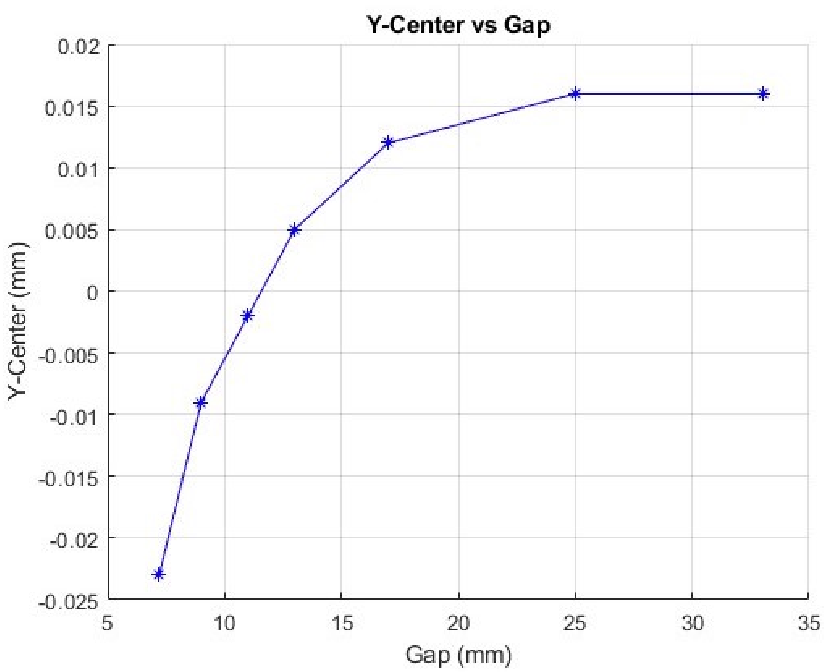

Figure 8: Magnetic axis position vs gap.

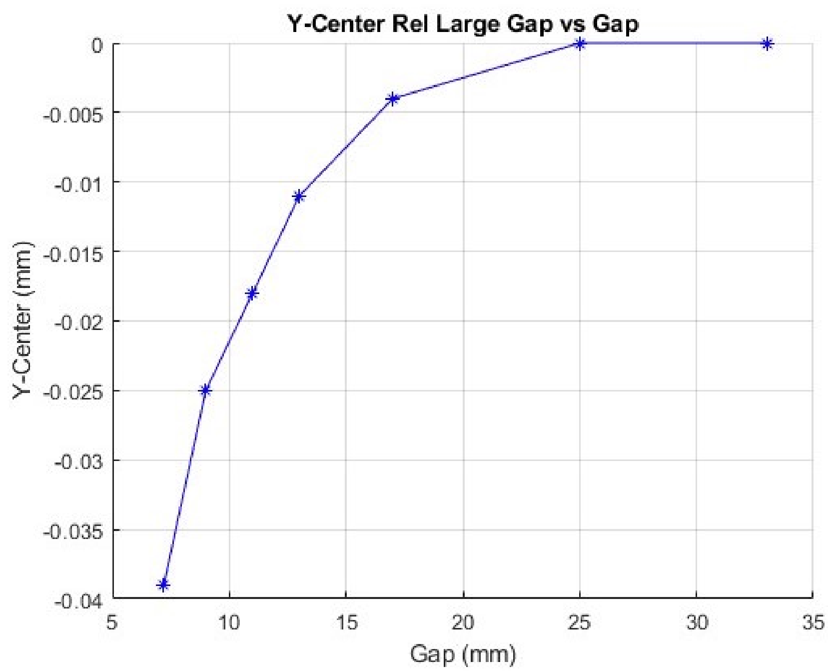

Figure 9: Magnetic axis position vs gap with the position at 33 mm gap used as the reference.

5 Source Of The Midplane Shifts

In order to understand why the midplane encoder correction did not work, we must understand the source of the shifts in midplane position. Since the midplane position is determined by the upper jaw position, we must understand how the upper jaw position is determined. In particular, we must understand the drivetrain for the upper jaw and how it behaves under loads.

The drivetrain of the upper jaw is shown in Figure 10. The upper jaw of the undulator

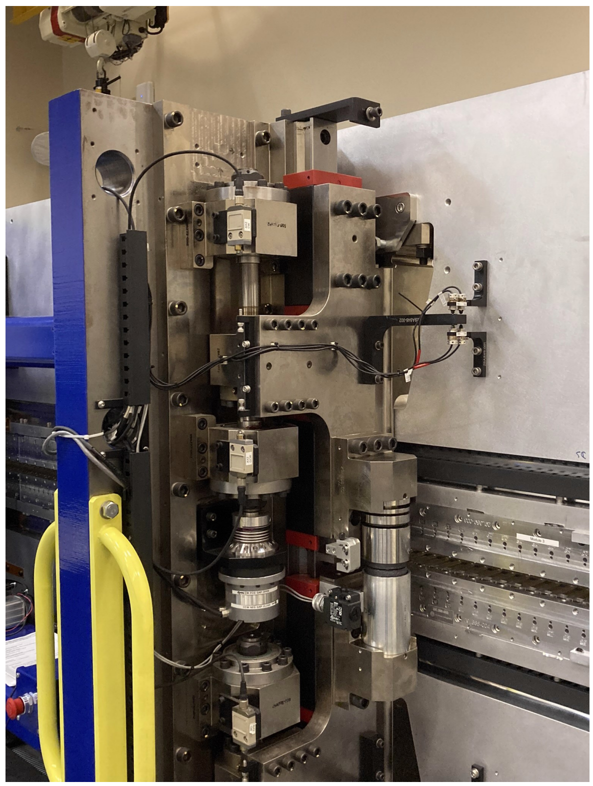

Figure 10: Drivetrain of the downstream side of the upper jaw of HE-SXU-000.

is held up through flexures by a large plate which is bolted to a pair of slides which take up moment loads and a screw which takes up vertical loads. The motor turns the screw to set the position of the top jaw. The drive is illustrated in Figure 11 where the main components are labeled.

We make a hypothesis for the midplane behavior that will be tested. Our hypothesis is that when vertical magnetic forces are applied to the upper jaw, the nut on the screw stays fixed, but the slides yield slightly causing the upper jaw to rotate about the center of the nut on the drive screw. The center of rotation is indicated by the red circle in Figure 11. The vertical and horizontal distances from the center of rotation to the support point for the upper jaw are indicated.

We now look for data to test the hypothesis given above. In particular, we can check

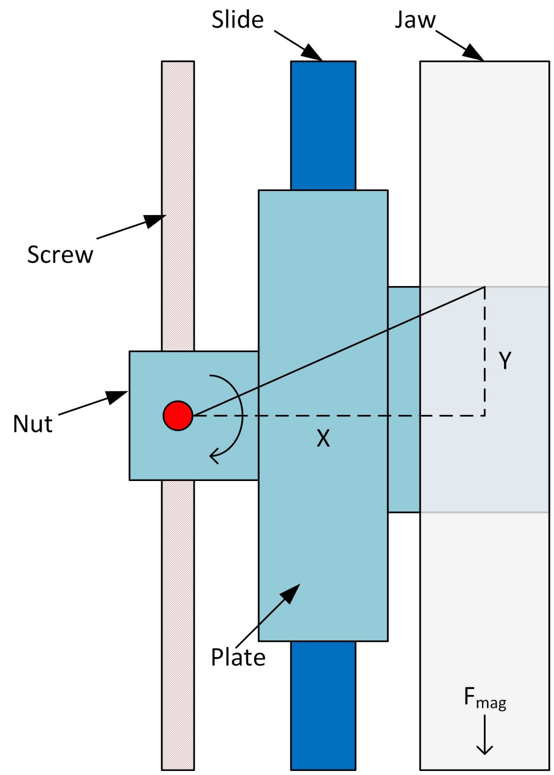

Figure 11: Schematic of the upper jaw drive system.

if it explains the shifts shown in Figure 1. If the hypothesis is correct, we can proceed to understand the midplane encoder results and the required corrections. We begin by considering the effect of a drive plate rotation.

The support point of the upper jaw moves according to the geometry of Figure 12. If the assembly rotates by $d\theta$ about the center of rotation and the jaw support point is a distance r away, the support point moves by a distance $r\,d\theta$. From the geometry shown in Figure 12, the upper jaw moves vertically by

$$dy = r\,d\theta\,\cos\theta \tag{2}$$

Since $x = r\cos\theta$,

$$dy = x\,d\theta \tag{3}$$

The touch probe measurements done on HE-SXU-000 allow the roll of the upper jaw to be computed. All the magnet poles were touched at two places separated in X. The changes in Y-position of the poles divided by the distance in X between touches gives the roll angle of the pole. An average was then taken over all the poles. The roll angle of the poles is the same as the roll angle of the upper jaw and the rotation angle of the drive plate. Figure 13 shows the roll of the upper jaw as a function of gap using the roll at 33 mm gap as a reference.

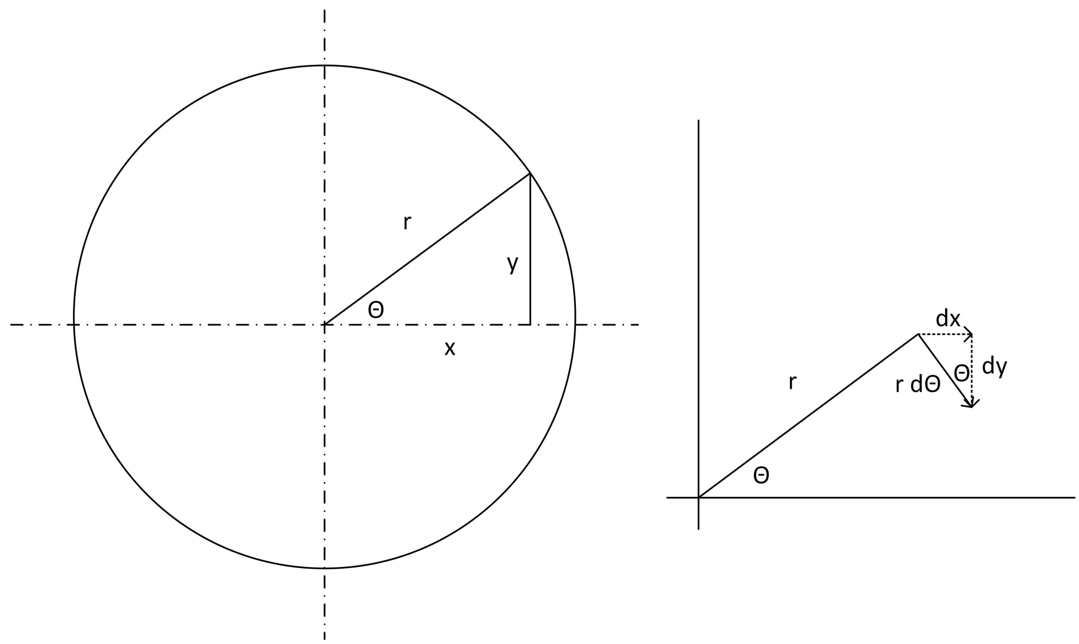

Figure 12: Geometry showing how the upper jaw rotates when magnetic forces are applied.

The upper jaw rolls because the plate holding the upper jaw rotates. This rotation causes the support point of the upper jaw to shift. We wish to see if the shift in the upper jaw support point agrees with the shift in the measured midplane position.

The horizontal distance from the center of the drive nut to the upper jaw support point was measured to be

$$x = 330 \text{ mm} \tag{4}$$

If we let $d\theta$ equal the measured roll angle of the upper jaw, which is equal to the rotation angle of the drive system plate, we can compare the measured vertical displacement of the midplane (Figure 1) to the calculated displacement of the upper jaw support point, $x\,d\theta$, where $d\theta$ comes from Figure 13. This comparison is done in Figure 14. The agreement is reasonably good. It seems that the shift in the undulator midplane is caused by the upper jaw moving down when the slides yield slightly due to the moment caused by the magnetic forces.

We made a hypothesis that roll of the upper jaw is responsible for the shifts of the undulator midplane. We take the agreement between the measured midplane shift and the calculated shift due to the measured roll angle as evidence that the hypothesis is correct. We can now proceed further to understand why the correction using the midplane encoders did not work.

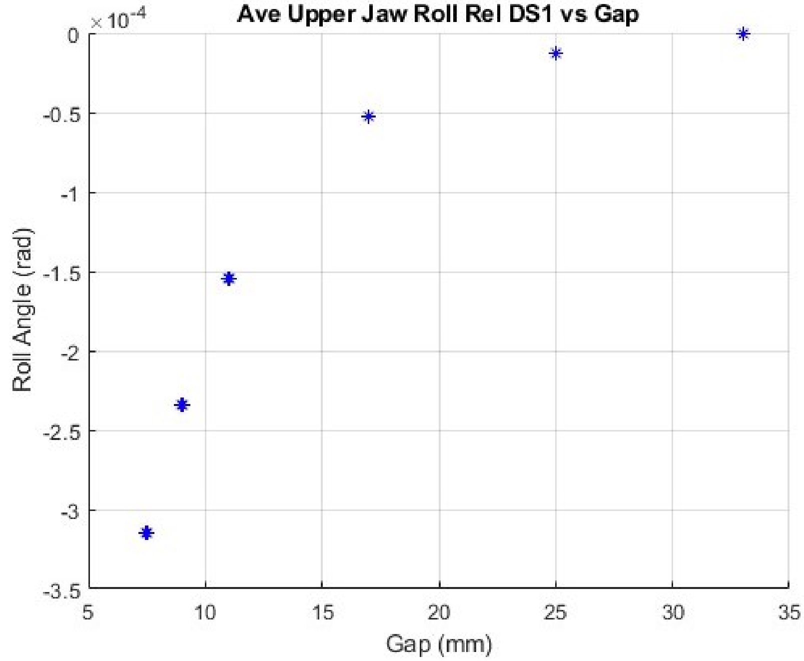

Figure 13: Roll of the upper jaw of the undulator as a function of gap.

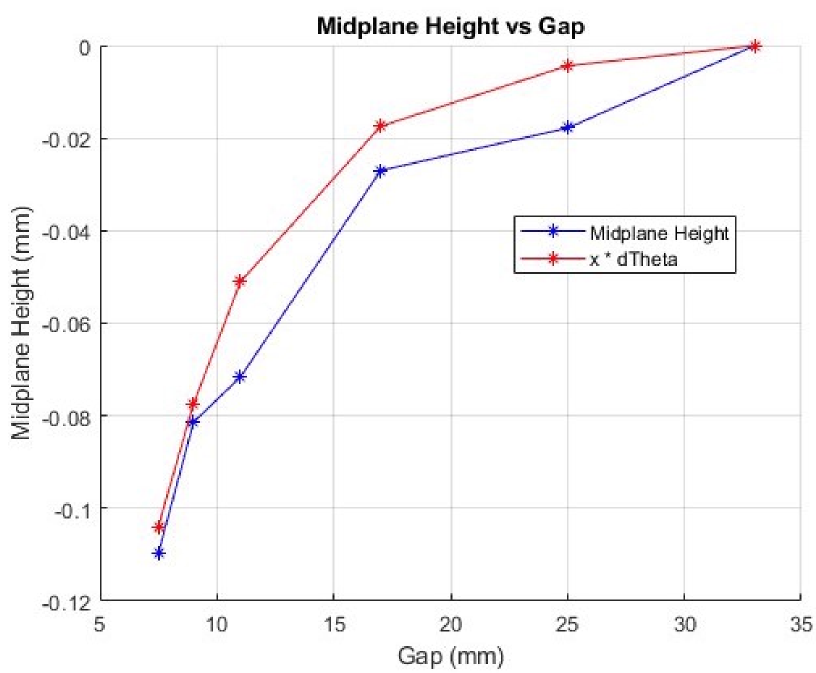

Figure 14: Comparison of midplane height to the vertical displacement of the upper jaw from the measured roll angle.

6 Analysis Of The Midplane Correction Performance

Many checks were made of our setup, and it was established that the midplane encoders and gap encoders were behaving properly. The change in midplane position must have a mechanical origin. Vertical shifts of the upper jaw would be seen by the midplane encoders. Roll effects of the upper jaw are not fully seen by the midplane encoders and can provide an explanation for the observed errors in the corrections.

The midplane encoder scale is not located horizontally in the middle of the jaw, but rather it is on the side of the jaw. The encoder scale position is illustrated in Figure 15.

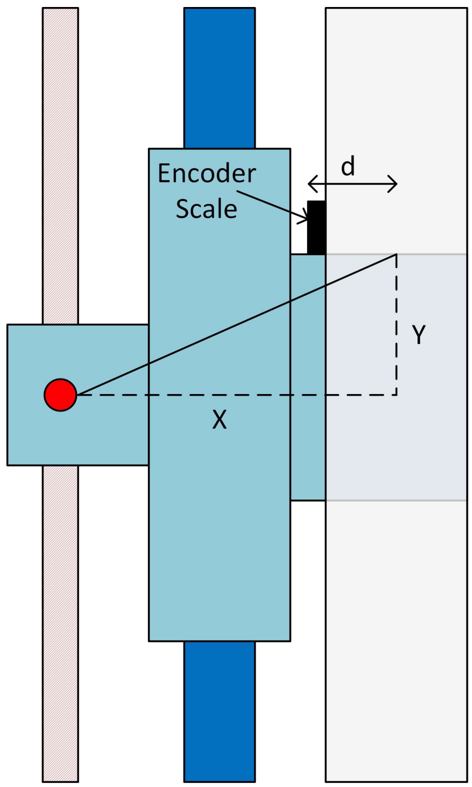

Figure 15: The midplane encoder scales are mounted on the side of the upper jaw.

The width of the jaw is 120 mm and the encoder scale is mounted on a plate 20 mm thick, so the midplane encoder scale is located a distance $d = 80$ mm from the center of the jaw.

When the drive plate and jaw roll by an angle $d\theta$, the midplane encoder scale moves by a distance dy given by

$$dy = (x - d)d\theta \tag{5}$$

The jaw center moves by $dy = xd\theta$. The resulting error in position from the midplane encoder measurement is the difference in these motions.

$$err = d\, d\theta \tag{6}$$

From this analysis, we expect that after the initial midplane encoder correction, the midplane is shifted by the error in the correction, $err = d\,d\theta$, as the gap is closed. To test this numerically, both the midplane position after correction and the calculated error in the correction, $d\,d\theta$, are plotted on the same plot using a value of $d = 80$ mm. This is shown in Figure 16. The curves match reasonably well. It appears that roll of the upper jaw and

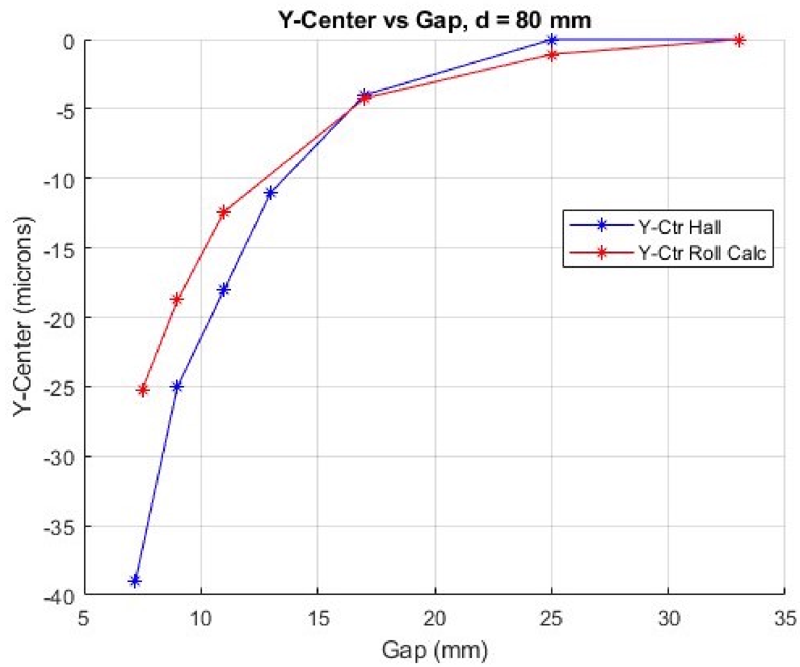

Figure 16: The midplane position and the calculated midplane position from roll of the top jaw are shown together.

the fact that the center of the jaw moves a different amount under roll than the encoder scale is causing errors in the calculated midplane correction.

The differences in the plot at small gap are explained by a more detailed analysis of the drive system given at the end of this note. One may wonder about the fact that the gap is measured at the ends of the undulator while the midplane encoder values are measured at the frame. The jaws bend under load as shown in Figure 17. The gap, however, only changes by about 5 microns going from the midplane encoders to the ends of the undulator. The gap used in the calculation $Y_{mid} = Y_{top} - G/2$ should refer to the mean gap, which is smaller than the gap at the ends for small gap as shown in the figure. This error would make the measured midplane position too high. These differences should only account for changes up to 10 microns in the calculated midplane position. We ignore these differences and focus on the roll of the upper jaw causing the jaw center to move a different amount than the midplane encoder scale used to correct it.

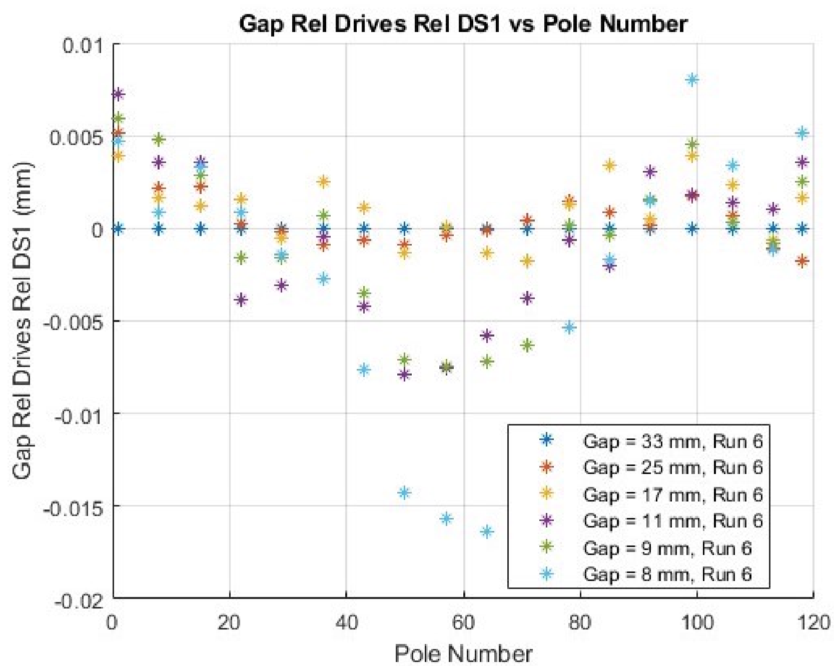

Figure 17: Gap deformation as a function of position for HE-SXU-000.

7 Midplane Correction Accounting For Upper Jaw Roll

We have seen that with no correction the midplane moves down by 110 microns as the gap is closed. With a correction using the midplane encoders at face value, the midplane moves down by 40 microns. A better error correction is required to reduce the 40 micron error.

Suppose the undulator upper jaw is put in a reference position as illustrated in Figure 18 with labels which have the subscript 0. Let N be the vertical position of the drive nut

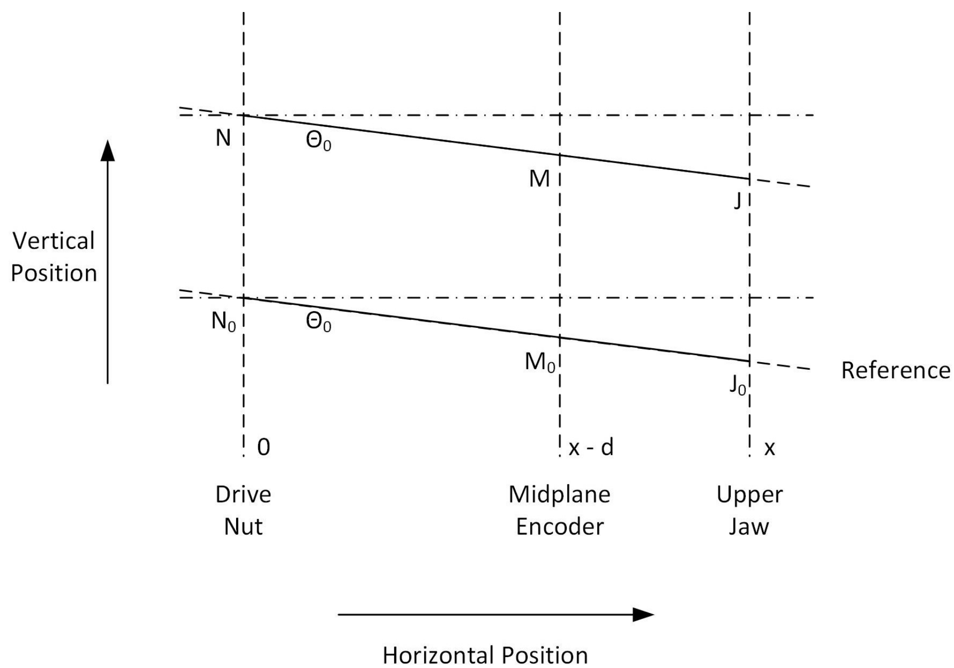

Figure 18: Ideal upper jaw motion with no angular deflection.

at horizontal position 0. M is the vertical position of the midplane encoder at horizontal position $x - d$. J is the vertical position of the upper jaw at horizontal position x. In the reference configuration, these positions are N_0, M_0, and J_0, respectively. The angle of a line through the drive system from the nut to the jaw in the reference configuration is θ_0.

Now suppose the gap is opened. Ideally, the angle of the line through the drive system does not change. In this ideal case

$$N - N_0 = M - M_0 = J - J_0 \tag{7}$$

The drive opens the gap without angular rotation. The midplane encoder accurately gives the distance the upper jaw has moved.

Now consider the actual case as illustrated in Figure 19. In this case the drive nut moves the same distance but the rotation in the drive system causes the midplane encoder and jaw to move by different amounts.

Let θ be the new angle of the line through the drive system and $d\theta = \theta - \theta_0$. The

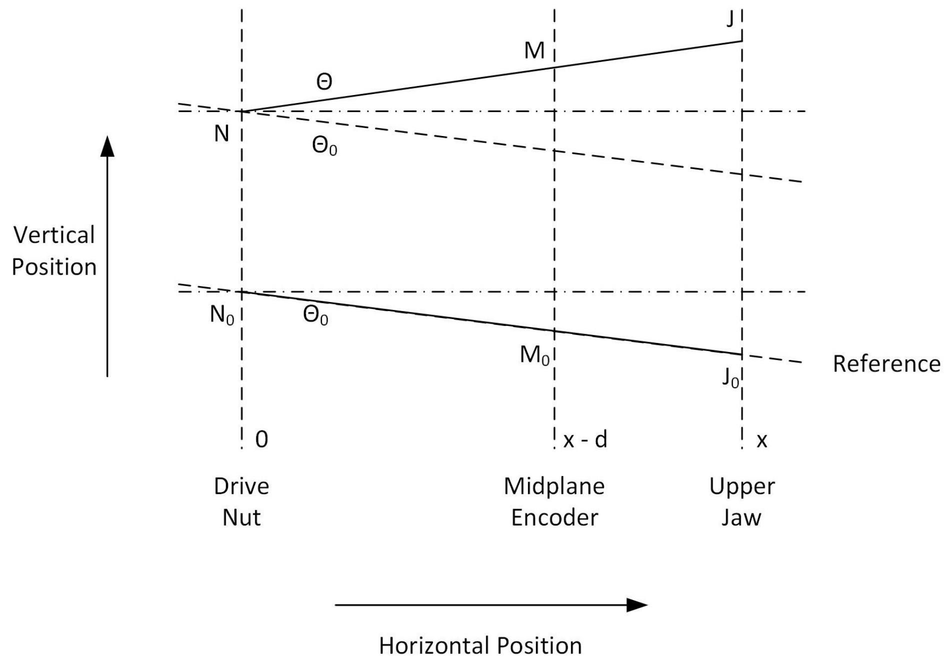

Figure 19: In the actual case, as the drive opens the gap, it rotates about the drive nut.

midplane encoder moves vertically a distance

$$M - M_0 = N - N_0 + (x - d)d\theta \tag{8}$$

The upper jaw moves vertically a distance

$$J - J_0 = N - N_0 + x\,d\theta \tag{9}$$

Our goal is to have the jaw move by the amount $N - N_0$, the same as it would move without rotation. The actual move differs by the amount $x\,d\theta$. We can apply a correction by shifting the drive nut by

$$dy = -x\,d\theta \tag{10}$$

as shown in Figure 20. This is a small move and we neglect any change in rotation angle during this move. The jaw moves to position $J' = J + dy$, such that

$$\begin{aligned} J' - J_0 &= J + dy - J_0 \\ &= N - N_0 + x\,d\theta + dy \\ &= N - N_0 \end{aligned} \tag{11}$$

We must now estimate $d\theta$ using the information we have. Using equation 8, we have

$$d\theta = \frac{1}{(x - d)}\left[(M - M_0) - (N - N_0)\right] \tag{12}$$

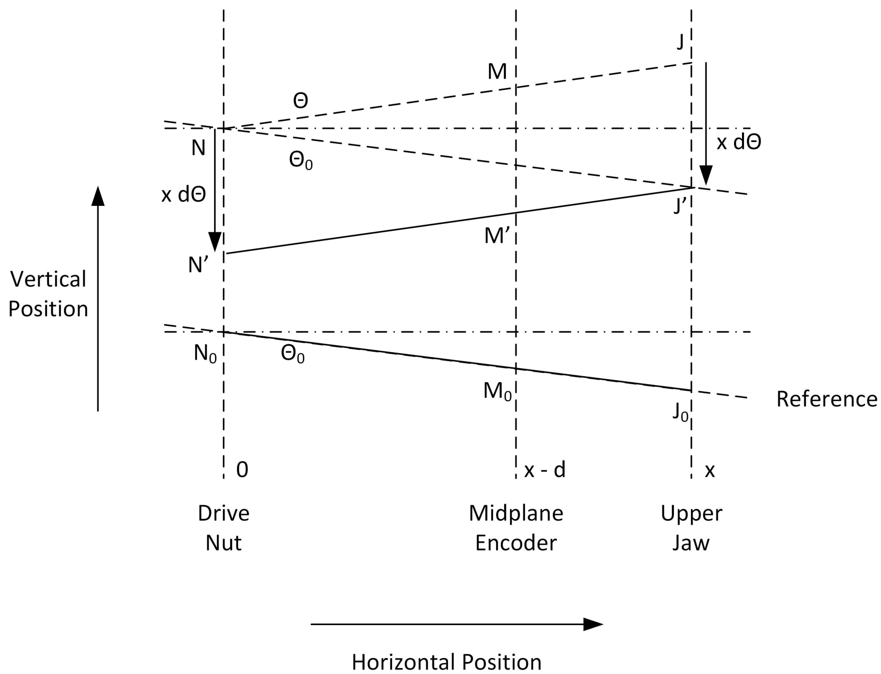

Figure 20: Apply a correction for the angle change by moving the drive nut to N', which moves the jaw to J', where $J' - J_0 = N - N_0$.

We want to move the drive by $dy = -x\,d\theta$. Using this expression for $d\theta$, we have

$$dy = -\frac{x}{(x-d)}\left[(M - M_0) - (N - N_0)\right] \tag{13}$$

In our original hypothesis we assumed that the error in the midplane position was due to the rotation in the drive system. Continuing along this line, we assume that the control system moves the drive nut by half the gap change. This assumption is plausible given the high precision of the drive components. With this assumption

$$N - N_0 = \frac{1}{2}\,(G - G_0) \tag{14}$$

Inserting this in equation 13 gives

$$dy = -\frac{x}{(x-d)}\left[(M - M_0) - \frac{1}{2}\,(G - G_0)\right] \tag{15}$$

The procedure we follow is then to set the gap by having the upper jaw move to half the gap value and the lower jaw move to make the gap correct. Then the angle error is corrected by shifting both the upper jaw and lower jaw by dy. This keeps the gap constant, and it keeps the midplane at the reference height.

Note that after the shift of the upper jaw by dy, the midplane encoder is at M', where

$$M' = M + dy \tag{16}$$

or

$$M' = M - \frac{x}{(x-d)}\left[(M - M_0) - \frac{1}{2}(G - G_0)\right] \tag{17}$$

So $M' - M_0 \neq \frac{1}{2}(G - G_0)$ as we had assumed when we initially corrected the gap using the midplane encoders.

We can calculate the correction numerically. Both x and d are known.

$$x = 330 \text{ mm} \tag{18}$$

$$d = 80 \text{ mm} \tag{19}$$

$$\frac{x}{(x-d)} = 1.32 \tag{20}$$

After the gap is set, the midplane encoders and gap encoders are read and the upper and lower jaws are shifted by

$$dy = -1.32\left[(M - M_0) - \frac{1}{2}(G - G_0)\right] \tag{21}$$

In practice one might want to set the midplane encoder offsets so

$$M_0 = G_0/2 \tag{22}$$

In this case the roll angle correction is

$$dy = -1.32\left(M - \frac{1}{2}G\right) \tag{23}$$

8 Test Of The Roll Angle Correction

We can check the new correction which includes roll effects using the data already presented. We know the midplane position without correction. We also know the midplane position after a correction was made where $dy = -(M - G/2)$ which led to 40 micron errors. The difference in these measured midplane positions gives us the distance the midplane was moved, i.e. $dy = -(M - G/2)$. Note that after this move the midplane encoder read $M'' = M + dy = G/2$. If we scale this shift by a factor of 1.32, we should arrive at a midplane position of zero. The results of doing this procedure are shown in Figure 21.

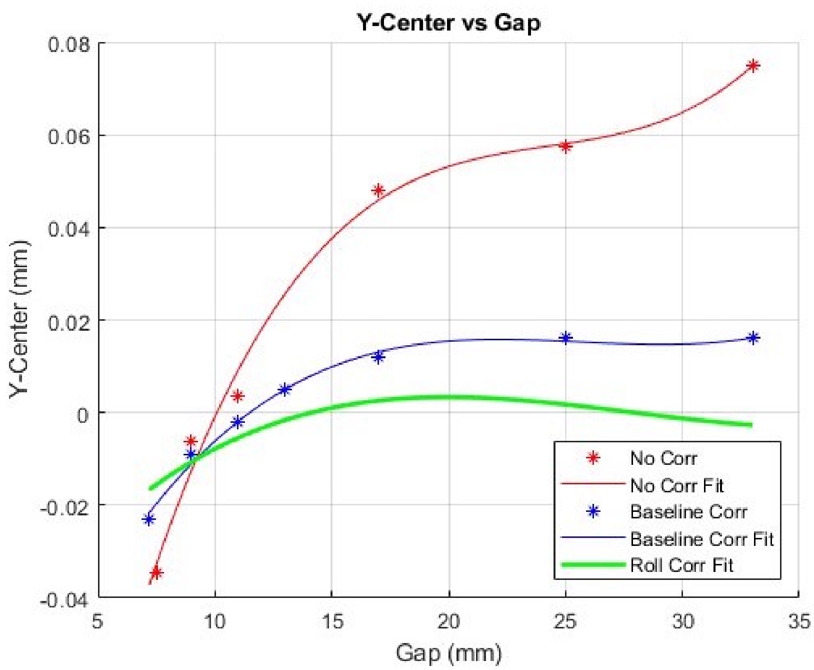

Figure 21: Check of the roll correction.

The red curve in Figure 21 shows the touch probe data and a third order fit. No midplane correction was done and no reference value was subtracted. The fit was done so that points could be subtracted at the same gap. The blue curve shows the Hall probe magnetic center results and a third order fit. Both jaws were moved so that the gap stayed constant and the midplane encoders read $M'' = G/2$. The difference between the blue curve and the red curve is the distance the midplane was moved. We found that this distance should be corrected by a factor of 1.32 in order to do a roll correction to account for the different horizontal positions of the midplane encoders and the center of the jaws. When the factor of 1.32 is applied to the distance the midplane was moved, the green curve results. The values are very close to zero. Relative to a reference value at large gap, the green curve varies by less then 15 microns over the gap range. With the factor of 1.32, the magnetic axis is within 15 microns of the probe path over the gap range. This is a small deviation.

There is some discrepancy at small gap. It appears that the alignment crew set the midplane to zero at 10 mm gap ($y = 0$ on red curve). The midplane encoders look like they were not set to half the gap at this point, but rather at a gap of about 12 mm ($y = 0$ on blue curve). These discrepancies can be fixed in future data sets. Overall, the roll correction factor of 1.32 makes a significant improvement.

9 Refinement Of The Roll Angle Correction

In reviewing this note, Diego Arbelaez pointed out a refinement to the roll angle correction that can be made. When the upper jaw has the magnetic forces applied by the lower jaw, the plate holding the upper jaw bends slightly. This is shown in Figure 22.

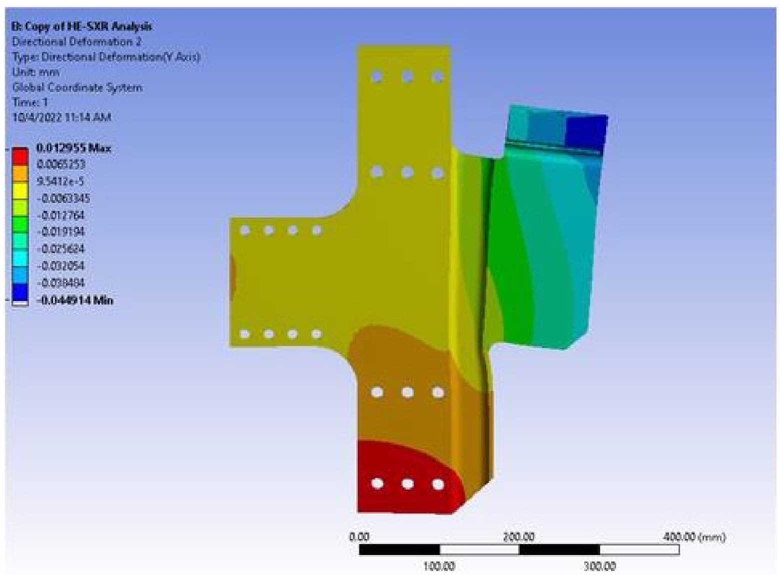

Figure 22: The flexure holding the upper jaw bends under load as shown in this Ansys model courtesy of Diego Arbelaez.

The effect of this bend is shown in Figure 23. The bending of the plate in the area of the flexure causes the upper jaw to roll by an additional angle $d\phi$. The center of rotation for the angle change is a distance f from the center of the jaw. In this case equations 8 and 9 become

$$M - M_0 = N - N_0 + (x - d)d\theta + (f - d)\, d\phi \tag{24}$$
$$J - J_0 = N - N_0 + x\, d\theta + f\, d\phi \tag{25}$$

Since the bending of the drive plate near the flexure and the compliance in the drive system slides are both small deformations, we assume they are linearly related to the applied magnetic force. In this case the angles $d\phi$ and $d\theta$ are linearly related. Let α be the proportionality factor.

$$d\phi = \alpha\, d\theta \tag{26}$$

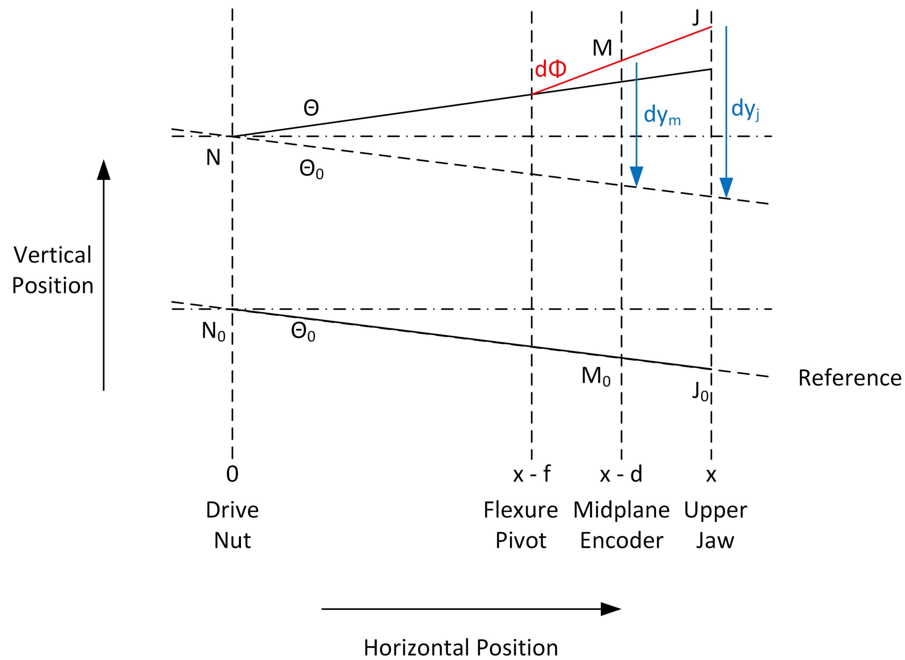

Figure 23: The plates holding the upper jaw bend slightly under load.

The equations for the midplane encoder reading and the jaw position are now

$$M - M_0 \quad = \quad N - N_0 + [(x-d) + \alpha\,(f-d)]\,d\theta \tag{27}$$
$$J - J_0 \quad = \quad N - N_0 + (x + \alpha f\,)\;d\theta \tag{28}$$

The correction required to make $J - J_0 = N - N_0$ is to move the drive nut by

$$dy = -\,(x + \alpha f\,)\;d\theta \tag{29}$$

Getting the angle $d\theta$ from the midplane encoder equation, we have

$$dy = -\frac{(x + \alpha f\,)}{[(x-d) + \alpha\,(f-d)]}\,[(M - M_0) - (N - N_0)] \tag{30}$$

As before, we assume $N - N_0 = \frac{1}{2}\,(G - G_0)$, so

$$dy = -\frac{(x + \alpha f\,)}{[(x-d) + \alpha\,(f-d)]}\left[(M - M_0) - \frac{1}{2}\,(G - G_0)\right] \tag{31}$$

The value of f comes from the Ansys model. Diego finds

$$f = 190\ \text{mm} \tag{32}$$

Now we must estimate the value of α. The Ansys model says that at 7.5 mm undulator gap, the drive plate near the flexure bends by $d\phi = -1.20 \times 10^{-4}$ rad. The touch probe measured an upper jaw roll angle of $d\theta + d\phi = -3.25 \times 10^{-4}$ rad at 7.5 mm gap. The angular deflection from the slides is then $d\theta = -2.05 \times 10^{-4}$ rad. The value of α is then

$$\begin{aligned} \alpha &= \frac{d\phi}{d\theta} \\ &= 0.58 \end{aligned} \tag{33}$$

Using the values for x, d, α, and f, we find

$$\frac{(x + \alpha f)}{[(x - d) + \alpha (f - d)]} = \frac{330 + 0.58 \times 190}{(330 - 80) + 0.58 \times (190 - 80)} \tag{34}$$

$$= 1.40 \tag{35}$$

The vertical correction after the gap is set is then

$$dy = -1.40 \left[(M - M_0) - \frac{1}{2} (G - G_0) \right] \tag{36}$$

and if $M_0 = G_0/2$

$$dy = -1.40 \left(M - \frac{1}{2} G \right) \tag{37}$$

A new test of the midplane correction was generated using this formula. The results are shown in Figure 24. The blue curve has been shifted so that the midplane encoders are equal to half the gap at 10 mm gap instead of 12 mm gap. The new factor of 1.40 has been applied. The midplane stays at $Y_{mid} = 0$ within 8 microns, which we consider negligible error.

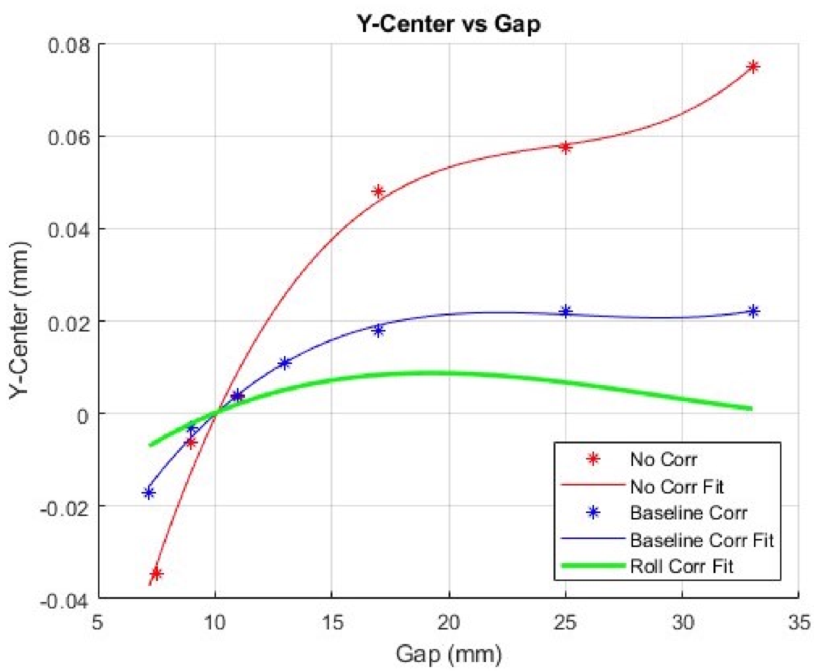

Figure 24: Midplane roll correction after the flexure bending is taken into account.

10 Conclusion

Without correction, the undulator midplane moves down by approximately 110 microns as the gap is closed. Measurements off the midplane by this amount would cause a large error in the measured K value. A simple correction using the midplane encoders at face value keeps the midplane position constant to about 40 microns. One wonders why the correction does not fully work. An argument was made that roll of the upper jaw causes the shift. The midplane encoders are on the side of the strongback about 80 mm away from the center of the jaw. This distance causes the scale of the midplane encoder to move less than the center of the jaw. When the midplane is shifted to apply the correction, the move is not large enough and a residual displacement of the midplane remains. To correct for this effect, a scaling factor of 1.40 should be applied:

$$dy = -1.40 \left(M - \frac{1}{2} G \right) \tag{38}$$

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