VIBRATING WIRE R&D FOR ALIGNMENT OF MULTIPOLE MAGNETS IN NSLS-II*

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Abstract

The alignment tolerance for a string of quadrupoles and sextupoles on a ~5 m long girder in the proposed light source NSLS-II at BNL is ±30 μm. In view of difficulties in achieving this tolerance by conventional fiducialization and survey, it is decided to align several magnets installed on a girder based on magnetic measurements using the vibrating wire technique. In order to develop the technique with improved accuracy and to ultimately build a fully automated system suitable for large scale production work, an R&D program has been ongoing at BNL. Results obtained using an R&D set up in both quadrupole and sextupole magnets are presented.

INTRODUCTION

National Synchrotron Light Source-II (NSLS-II) is a proposed 3 GeV storage ring designed to deliver high brightness and flux [1]. Due to the rather large (>50) closed-orbit amplification factors for random quadrupole misalignments and strong sextupoles, the alignment tolerances are very tight (±30 μm) for a set of multipoles on a girder. Such tolerances are hard to achieve by fiducializing each magnet and then using survey to install the magnets on a girder. It is, therefore, desirable to align the magnets on a girder directly using a suitable magnetic measurement technique. This would also relax machining tolerances for the girder, resulting in significant cost savings. In view of the typical girder length of ~5 m, a vibrating wire technique [2-4] was considered to be the most suited for this task. It is interesting to note that the proposed Taiwan Photon Source is also considering using the vibrating wire technique to align multipoles [5].

In order to systematically study and improve the resolution and absolute accuracy achievable with the vibrating wire technique in quadrupoles and sextupoles, and also to develop a fully automated system suitable for large scale production measurements, an R&D effort is underway at Brookhaven National Laboratory (BNL). The newly designed and built R&D system will be described and some results obtained in quadrupoles and sextupoles will be presented in this paper.

THE VIBRATING WIRE TECHNIQUE

The basic setup for a vibrating wire measurement is shown schematically in Fig. 1. A thin (0.125 mm diameter typical) Cu-Be wire is stretched through the aperture of the magnet(s) to be measured. The two ends of the wire are supported on X-Y translation stages. A suitable weight keeps the wire in tension. A pair of wire vibration sensors detects the motion of the wire in both horizontal (X) and vertical (Y) direction. The magnet is mounted on precision movers to align its magnetic axis to a line defined by the wire ends.

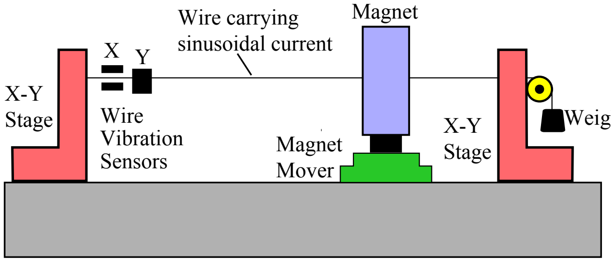

Figure 1: Basic set up for vibrating wire measurements

When the wire carries a sinusoidal current, it experiences a periodic force due to any magnetic field present along its length and begins to vibrate. By matching the frequency of the current to one of the resonant modes of the wire, and choosing a mode that has an antinode near the axial center of the magnet being measured, the sensitivity can be significantly enhanced, allowing even very weak fields to be detected. If the wire is moved across the aperture in the horizontal or vertical direction, the field seen by the wire, and hence the amplitude of vibration, varies as a function of the offset from the magnetic center. Such a scan provides the field profile across the aperture, from which the magnetic center position can be derived. More details about the technique can be found in [2-4].

VIBRATING WIRE R&D SETUP AT BNL

Before adopting the vibrating wire technique for the production phase of the project, it was necessary to carry out a detailed study of systematic and random errors in the measurement of quadrupoles and sextupoles to ensure that the required tolerances for NSLS-II could be met. A new setup for this R&D was designed and built. Since we do not yet have prototype magnets for the NSLS-II project, we have obtained sextupole and quadrupole magnets on loan from the Swiss Light Source [6]. One quadrupole and one sextupole magnet is mounted on

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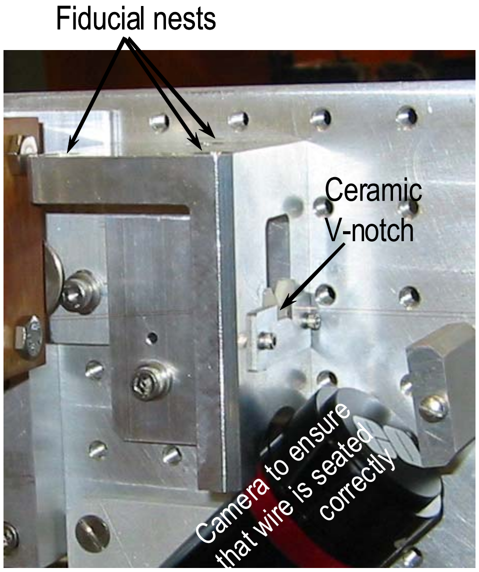


Figure 2: Wire end details.

manually operated magnet movers on top of a large granite table. These movers use a differential screw mechanism to allow coarse and fine adjustment of the magnet position with a resolution of ~ 1 μm. Ceramic V-notches mounted on two computer controlled X-Y stages define the ends of the wire (Fig. 2). The wire ends can be located in space by surveying a set of fiducials rigidly attached to the V-notch holders. In the present setup, the wire length between the two V-notches is 7.3 m, which is similar to what may be used in production to measure ~5 m long girders. Wire vibration detectors consist of two LED-phototransistor assemblies [7] – one for each axis, mounted as shown in Fig. 3. A unique feature of the BNL R&D setup is that a set of vibration sensors is provided on both ends of the wire. This gives two simultaneous, independent measurements of the magnetic axis, allowing consistency checks of the results.

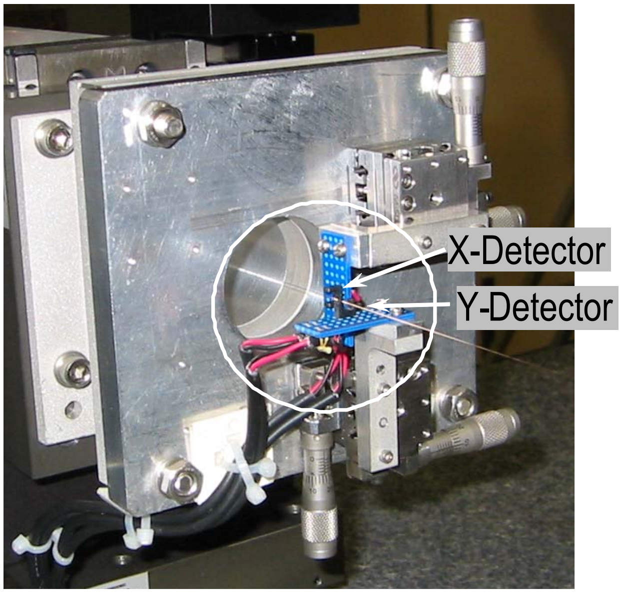


Figure 3: Wire vibration sensors.

DATA ACQUISITION AND ANALYSIS

The current in the wire is driven by a HP33120A signal generator. The signals from all the four vibration sensors are acquired, along with the drive current, using a 16-bit ADC. Data presented in this paper were acquired for 100 cycles with 40 points recorded per cycle. The data are taken at many drive frequencies around the resonance to obtain a full resonance curve, from which parameters such as resonance frequency and amplitude are derived using a least squares fit to the expected theoretical form [2].

For measurement of any magnet, the wire is moved to several positions in the horizontal and vertical directions and the vibration amplitude measured at each position by carrying out a frequency scan. The resulting horizontal and vertical field profiles are analyzed to obtain the magnetic center.

Sag correction

For a 7.3 m long Cu-Be wire, there is significant sag, ~550-600 μm, even with a tension very close to the breaking point. As a result, accurate correction for sag must be made to achieve the desired alignment accuracy. The sag, s, can be computed from the measured fundamental resonance frequency using the relation

$$s = \frac{g}{32 f^2} \qquad (1)$$

where g is the acceleration due to gravity and f is the fundamental resonance frequency. For precise estimate of the sag, the resonant frequency must be accurately determined (to about ±0.02 Hz) and it must remain stable over the duration of the measurement. Fig. 4 shows the sag computed from the resonance frequency over a period of several days, indicating very good stability, with the exception of an abrupt change of about 10 μm from one day to another. The reason for this change is not known. However, the results from the two sensors used in this study are very consistent. It should be noted that the resonance frequency is automatically derived from each data set measured, and is thus continuously monitored. This relaxes the need for long term stability of the resonant frequency since a complete scan typically takes only about 30 minutes or less.

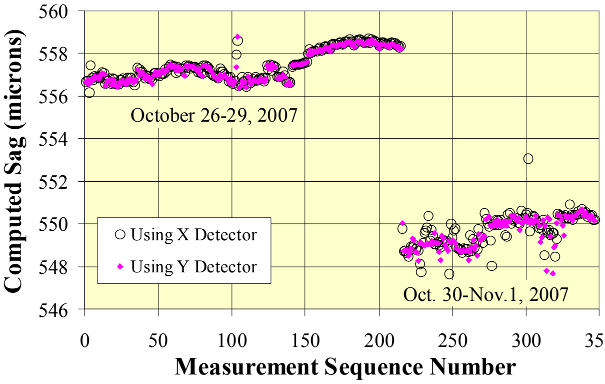


Figure 4: Stability of wire sag, as derived from the measured resonant frequency, over several days.

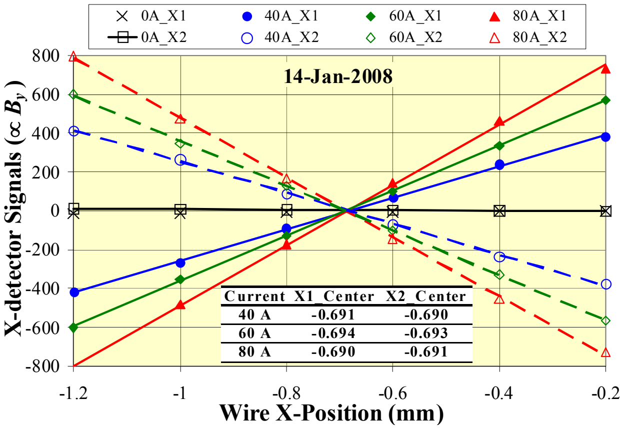
RESULTS IN A QUADRUPOLE MAGNET

In the case of a quadrupole magnet, the vertical and the horizontal field components, B_y and B_x, vary linearly with the horizontal and vertical offsets from the center:

$$B_y = G(x - x_0); \quad B_x = G(y - y_0) \tag{2}$$

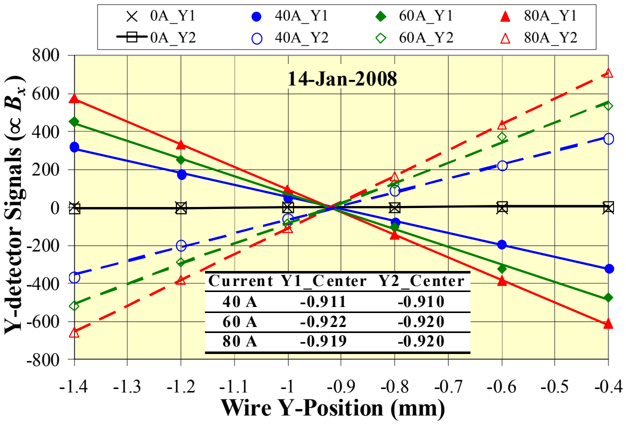
where G is the quadrupole gradient and (x_0, y_0) is the location of magnetic axis in the coordinate system defined by the X-Y stages of the vibrating wire system. The vertical field causes the wire to vibrate in the horizontal plane, and is picked up by the X-detector. Similarly, the horizontal field is picked up by the Y-detector.

The apparent magnetic center of a quadrupole is affected by any background fields, such as the earth's field, or the remnant field in other magnets on the girder which is also seen by the wire. One way to correct for this background field is to do a scan with the quadrupole unpowered, and then subtract the background data from a field profile measured with the quadrupole powered. One could also do this at several different currents to study the variation, if any, of the magnetic center with excitation. As long as one is well within the saturation range of the iron yoke, it is expected that the true quadrupole center will be independent of the magnet excitation.



Current	X1_Center	X2_Center
40 A	-0.691	-0.690
60 A	-0.694	-0.693
80 A	-0.690	-0.691

Figure 5: X-detector signals in horizontal scans using mode = 10 in a quadrupole powered at different currents.



Current	Y1_Center	Y2_Center
40 A	-0.911	-0.910
60 A	-0.922	-0.920
80 A	-0.919	-0.920

Figure 6: Y-detector signals in vertical scans using mode = 10 in a quadrupole powered at different currents.

Figs. 5 and 6 show the results of horizontal and vertical scans in a SLS quadrupole powered at various currents, including 0 A. The slopes of the lines are proportional to the quadrupole gradient (see Eq. 2), which is 13.8 T/m at 80 A. The magnetic center at any current is defined as the intersection of the corresponding line with the 0 A line. The centers measured by the detectors on the two ends are tabulated in Figs. 5 and 6, and agree with each other within ~1 μm at any given current. The standard deviation of 10 consecutive measurements was found to be ~7 μm, which shows that the reproducibility is well within the required tolerance.

RESULTS IN A SEXTUPOLE MAGNET

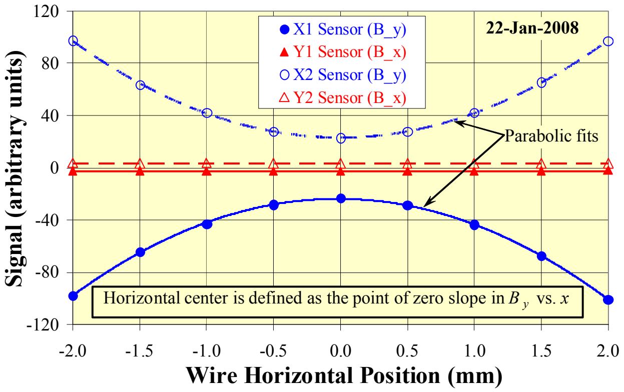
In the case of a sextupole magnet, the vertical and the horizontal field components, B_y and B_x, are given by:

$$B_y = B_3\left[\frac{(x - x_0)^2 - (y - y_0)^2}{R_{ref}^2}\right] \tag{3}$$

$$B_x = 2B_3\left[\frac{(x - x_0)(y - y_0)}{R_{ref}^2}\right] \tag{4}$$

where B_3 is the sextupole field at a reference radius of R_{ref} and (x_0, y_0) is the location of magnetic axis in the coordinate system defined by the X-Y stages of the vibrating wire system. B_y varies quadratically with x for any given value of y. It also varies quadratically with y for any given value of x. The magnetic center of a sextupole is defined by the point where the normal quadrupole given by dB_y/dx $(= dB_x/dy)$ and the skew quadrupole given by dB_x/dx $(= -dB_y/dy)$ are zero. The magnetic center can either be measured by doing horizontal and vertical scans for B_y and fitting the profiles to parabolic forms, or by measuring the B_x profiles, and determining the point where B_x has zero slope along both axes.

Figs. 7 and 8 show the results from horizontal and vertical scans in a SLS sextupole powered at 80 A. The value of B_3 / R_{ref}^2 at this current is 215 T/m^2. These results show that the horizontal and vertical field profiles



Horizontal center is defined as the point of zero slope in B_y vs. x

Figure 7: Results from a horizontal scan using mode = 6 in a sextupole powered at 80 A. The Y-position for this scan is nominally at the magnetic center, resulting in zero slope for the B_x component.

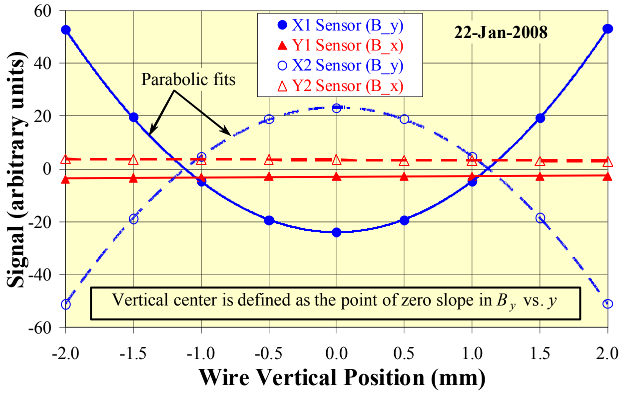


Figure 8: Results from a vertical scan using mode = 6 in a sextupole powered at 80 A. The X-position for this scan is nominally at the magnetic center, resulting in zero slope for the B_x component.

are in agreement with the expectations from Eqs. (3) and (4). The magnetic centers derived from the sensors on the two ends show good agreement for the vertical position, but agree only within ~ 15 µm for the horizontal position. The exact reason for this disagreement is not known, and is still under investigation.

The analysis of parabolic fits in Figs. 7 and 8 makes use of only the horizontal motion detectors. One could also use the data from the vertical motion detectors and use the B_x profiles instead to determine the magnetic center. This requires several horizontal and vertical scans to be performed in order to find the center. Each such scan gives a straight line whose slope is proportional to the offset along the other axis. As an example, Fig. 9 shows the horizontal field profile as a function of vertical position for $x = 0$ and $x = \pm 0.5$ mm. A linear dependence is seen in each case, with a slope that depends on the X-position. These slopes, derived from straight line fits, are plotted as a function of the X-position in Fig. 10. The horizontal center can be found by interpolating to zero slope. As seen from Fig. 10, the results from the sensors on the two ends of the wire are in excellent agreement. A similar procedure can be followed to obtain the vertical center using the vertical (B_x) sensors, and results from the two sets of sensors are again in very good agreement.

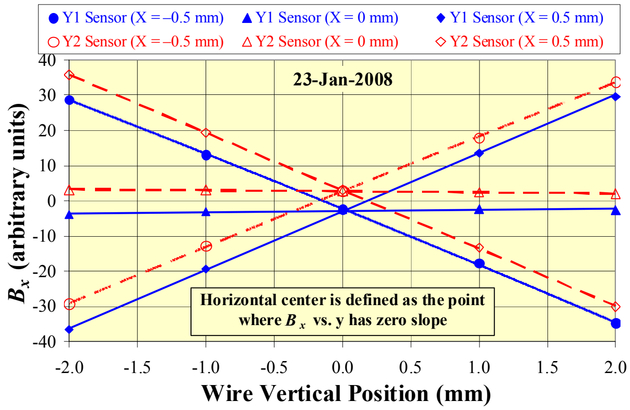


Figure 9: Horizontal field measured in vertical scans using mode = 6 at several values of x in a sextupole powered at 80 A.

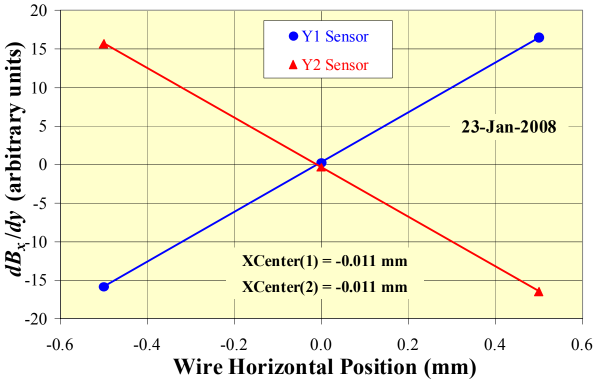


Figure 10: Slopes, dB_x/dy, derived from the data in Fig. 9, as a function of the X-position. The magnetic center is obtained by interpolating for zero slope.

In view of the inconsistencies seen in some of the sextupole data, we have also carried out measurements using mode = 8 instead of 6. All the sextupole measurements using different modes, as well as using different field components, are summarized in Table 1. In general, the results from the two sets of sensors agree very well using the B_x data, but not so well using the B_y data. In both cases, there is a systematic difference of ~15 µm between centers obtained using different modes. The reasons for these inconsistencies are still unknown, and are being studied.

Table 1: Summary of results in sextupole at 80 A

Quantity	Sensors Used	B_x data		B_y data	
		Mode 6	Mode 8	Mode 6	Mode 8
X_Center (µm)	Pulley end	-11	-25	6	-8
	Fixed end	-11	-24	-11	-25
Y_Center (µm)	Pulley end	12	-3	-2	-3
	Fixed end	12	-2	1	2

CORRELATION WITH MAGNET MOTION

We have studied the correlation of the magnetic center measured by the vibrating wire technique with small, known changes in the magnet position. For this study, several digital indicators (1 µm resolution, ~3 µm accuracy) were installed on the magnet and the magnetic center was measured using the vibrating wire technique. This served as the reference measurement. The magnet position was then changed in steps of ~20 µm using the digital indicators and the manual magnet movers. The magnetic center was measured again at each of the magnet positions and compared against the digital indicator readings. These studies were conducted at a time when the sensors on one of the ends were not yet commissioned. As a result, only one set of results were available from these studies.

Fig. 11 shows the correlation between magnetic center and the magnet position for a quadrupole magnet powered at 80 A for horizontal (circles) and vertical (triangles)

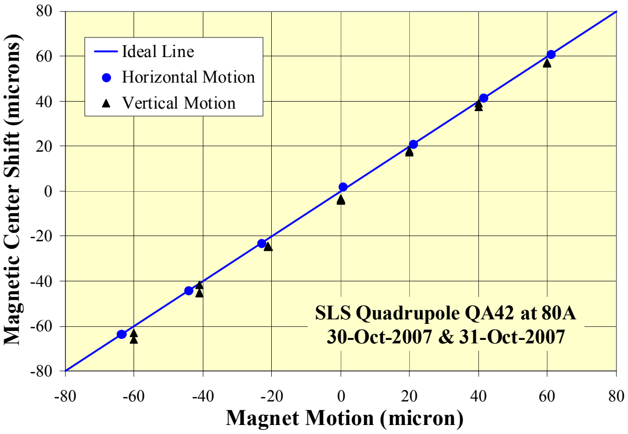


Figure 11: Correlation between shift in magnetic center and known motions of a quadrupole in horizontal and vertical directions.

motions. The solid line represents the case of perfect correlation between the two. The horizontal center is seen to correlate almost perfectly with the magnet motion. The vertical center also follows the magnet motion within 5 µm or less. These results, along with the data presented earlier on the quadrupole centers, show that the vibrating wire technique does have sufficient precision to align the quadrupoles well within the required tolerance.

Fig. 12 shows the correlation between magnetic center and the magnet motion in the case of a sextupole. Once again, a good correlation is seen between the horizontal motion and the magnetic center. However, all the data points for the vertical motion are systematically in error by about 13 microns. It is possible that the reference measurement is somehow in error by this amount, since the relative changes between different data points shown in Fig. 12 still correlate very well with the magnet motion. The dashed line in Fig. 12 represents the expected line under this assumption. Although it appears that the vibrating wire technique can be used for sextupoles with accuracy better than the required ±30 µm, it is clear that more work is still needed to resolve some inconsistencies and to further improve the accuracy and resolution.

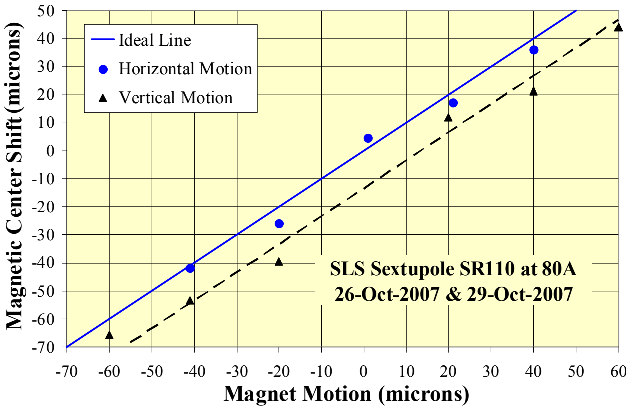


Figure 12: Correlation between shift in magnetic center and known motions of a sextupole in horizontal and vertical directions.

MAGNET ALIGNMENT ON A GIRDER

Magnets will be first installed on a girder and roughly aligned based solely on mechanical features and/or survey using laser trackers. The vacuum chamber will then be installed and sealed with end caps that have provision to install another tube for the wire. This will prevent any contamination of the vacuum chamber inner surface. It is expected that the magnets will be aligned to ±1 mm or better during this initial assembly. Special magnet movers (described in the next section) will then be installed on each magnet on the girder. The girder will then be installed on a vibrating wire test bench inside a temperature controlled (±0.1 C) room. Once the girder reaches a stable temperature, vibrating wire measurements will be carried out, powering only one magnet at a time, to determine the magnetic axis. The magnet will then be moved to align its axis to a straight line defined by the wire ends. This will also involve correction for the wire sag computed from the resonance frequency and the axial location of the magnet. The vibrating wire measurements will be repeated to confirm the alignment. After all the magnets on the girder are aligned, the magnets will be locked into place and the magnet movers will be removed. The girder will then be removed from the test bench and be ready for installation in the machine.

The success of the above alignment procedure depends on two key factors – the ability to move and then lock the magnets in place with a resolution of a few microns, and the stability of the alignment when the girder is transported from the test stand to the machine for installation. The first of these is addressed by appropriate design of the magnet movers and a “bolting test” carried out to study the ability to lock the magnets in place. This is described further in the next section. The second issue is not addressed yet, and will be studied when we will have a girder with prototype magnets available.

DESIGN OF MAGNET MOVERS

The main components of the magnet mover system are shown in Fig. 13. The system is comprised of commercially available ball screw jacks coupled to servo-motors. The platform supporting the magnet yoke rests on four cam followers. Through a lever system, the magnet center can be raised or lowered using four actuators with ~1 µm resolution. The motors can be operated either individually or in unison, based on the feedback from the vibrating wire measurements. A single actuator on only one side is used for lateral motion of the magnet. A preloaded spring mechanism on the other side prevents backlash during lateral movements. Also, a set of four L-shaped brackets with a rolling ball contact prevents any yaw from being introduced. LVDT sensors allow the magnet position to be displayed. This is necessary not just as a check that the system is operating properly, but also to allow the technicians to precisely maintain the positioning of the magnet during final bolting, when the magnet movers are removed. The

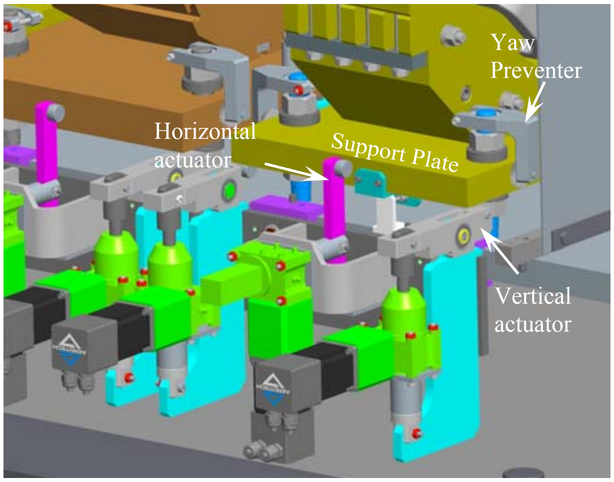


Figure 13: Design of magnet movers for alignment of multipoles on a girder.

magnet is ultimately held in place on the girder using only the bolts.

RESULTS OF BOLTING TESTS

To determine the feasibility of maintaining the required positional accuracy when anchoring individual magnets to the girder, a Bolting Test Fixture, suitable for a Swiss Light Source quadrupole magnet of size and weight comparable to the NSLS-II magnets, was fabricated. The initial version of the fixture did not have computer controlled movers. So, the magnet position was moved manually. Using digital dial indicators, 10 trials of positioning and then bolting the magnet were performed to replicate the procedure that will be followed with the magnet mover system. Magnet location data and time required per trial were recorded. These tests proved that it is relatively quick (less than 5 minutes per magnet) and easy (standard fine thread hardware, no special tools or experienced labor) to obtain a stable positioning of the magnet within ±3 μm vertically (usually much better than this), and within ±20 μm laterally of the desired theoretically "perfect" position with the proposed support system.

A second set of 10 trials on the same magnet was undertaken after installing the computer-controlled servo-motors and jacks, in order to prove out the automated system that will be used in the final alignment procedure with the vibrating wire. In this test, a LabView program controlled the motors instead of wire feedback. There were four vertically-operating jacks and two laterally-operating jacks. The current version of the design has only one lateral actuator, as described in the previous section. The system test showed that the automated design performs well. Bolted position in the vertical direction was reproduced within the same ±3 μm as before, and the lateral positioning accuracy was improved to within ±8 μm. Thus, the basic magnet mover design and the bolting technique developed should be able to meet the alignment requirements for NSLS-II.

SUMMARY

A new R&D setup has been designed and built at BNL for studying the accuracy and suitability of the vibrating wire technique for the challenging alignment requirements of NSLS-II. The magnetic center determined by vibrating wire tracks very well with magnet motion for a quadrupole. Redundant sensors in the BNL setup allow checks of consistency and absolute accuracy. In the case of sextupoles, certain discrepancies have been found between data taken using different sets of sensors. These discrepancies, although still below the requirements of NSLS-II, are being investigated to further improve the absolute accuracy of sextupole measurements. A design of magnet movers has been completed for the final positioning and locking of the magnets on a girder. A bolting test was performed, which validates the basic design of the magnet movers and the magnet support system concept itself.

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