OPTIMIZATION OF MAGNET STABILITY AND ALIGNMENT FOR NSLS-II*

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Abstract

The high-brightness design of the NSLS-II lattice limits uncorrelated vertical RMS motion of the multipole magnets on a girder to less than 25 nm. The stability of the girder-magnets assembly is affected by factors such as ambient ground motion and temperature fluctuations in the storage ring. The stability design optimization of the NSLS-II magnets and their girder support system is discussed in this paper and stability test results for a prototype girder-magnets assembly are presented.

INTRODUCTION

The NSLS-II, a new 3rd generation light source under construction at the Brookhaven National Laboratory, consists of a 3-GeV storage ring designed to provide an ultra high-brightness beam. The natural horizontal emittance of the beam is 2 nm but is expected to be below 1 nm when damping wigglers are installed. The vertical emittance is chosen to be 8 pm, the diffraction limit for 1 Angstrom radiation.

Stringent mechanical stability and magnet alignment requirements are specified for the storage ring magnets to produce a beam of this low emittance and reasonable lifetime. Mechanical stability tolerances, which cover both the vibration and thermal aspects, require uncorrelated RMS motion of less than 25 nm in the vertical direction. This is based on 10% of the minimum vertical size of the beam. The allowed RMS motion in the horizontal direction is 10 times larger corresponding to the beam size in this direction. The alignment tolerance between magnets on the same girder is ± 30 μm.

The design preferences for meeting the stability and alignment requirements are often contradictory. The NSLS-II girder support system is optimized to balance these requirements with a cost-effective design.

GIRDER SUPPORT SYSTEM DESIGN

A vibrating wire technique [1] has been adopted at NSLS-II to ensure precision alignment of the magnets to within ± 30 μm. This technique requires the alignment to be performed outside the storage ring tunnel in a temperature and humidity-controlled environmental room with a temperature stability of ± 0.1 °C. After the precision alignment the girder-magnet assembly is transported to the storage ring. A series of tests on the girder-magnet assembly showed that the gravity deflection of the assembly supported at the two ends had an unacceptable scatter of ~15 μm. This led to the concept of supporting the girder at multiple support points to further strengthen the stiff girder as shown in Figure 1. In addition, the top surface of the girder is surveyed to establish its profile after completing the precision alignment of the magnets. This profile will be reproduced in the storage ring after the tunnel temperature is stabilized to ± 0.1°C. The girder profiling is accomplished by laser trackers using fiducial mounts on the top surface of the girder directly above the height-adjustment bolts (Fig. 1).

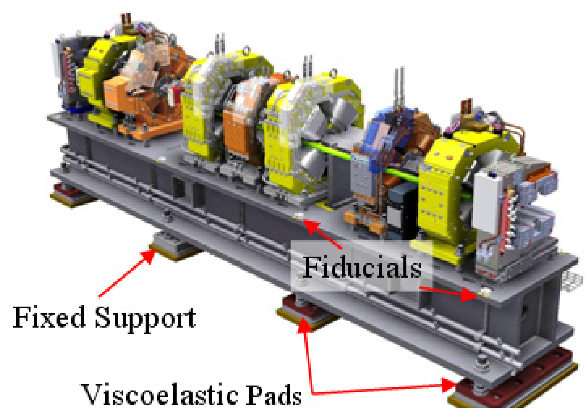

Figure 1: NSLS-II girder support system design.

The support points for every ~1.5 meter length of the girder also ensure that the natural frequencies of the girder-magnet assembly would be 30 Hz and above. This prevents amplification of the uncorrelated ambient floor motion below 30 Hz, which at the NSLS-II site is expected to be less than 20 nm. The ambient motion above 30 Hz (~1 nm) is not significant even when amplified as shown in the next section. The vibration stability criterion is, therefore, easily met with this over-constrained design of the support system.

The over-constrained girder, however, is not free to expand or contract with the tunnel temperature fluctuations. This introduces bending deformations in the girder, leading to magnets' misalignment, with the same time cycle as seen by the tunnel air (designed to be 1 hour for the NSLS-II tunnel). In order to prevent the girder from bending, viscoelastic pads (Fig. 1) are used between the floor and the girder at all supports-points except at one fixed support in the middle. These pads have the additional advantage of further suppressing the vibration amplification [2].

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AMBIENT FLOOR VIBRATION

The NSLS-II girder-magnet assembly is supported at eight locations on 2 inch-diameter bolts (overall length of the bolts is ~ 6"). A tightening torque of 1000 ft-lbs on these bolts is necessary to ensure a stiff system with a high natural frequency [3]. Through modal analyses and vibration tests (Fig. 2) it was established that for the NSLS-II girder-magnet assembly the first fundamental mode (rocking mode) of vibration has a natural frequency of ~30 Hz in which all the magnets move in phase. In the design of the girder we have incorporated seven one-inch-thick internal plates welded to the top and the two side plates of the girder. This enhances the torsional stiffness of the girder and consequently, the second mode (twisting mode) has a high frequency of ~50 Hz in which the magnets move out of phase (uncorrelated motion between the magnets).

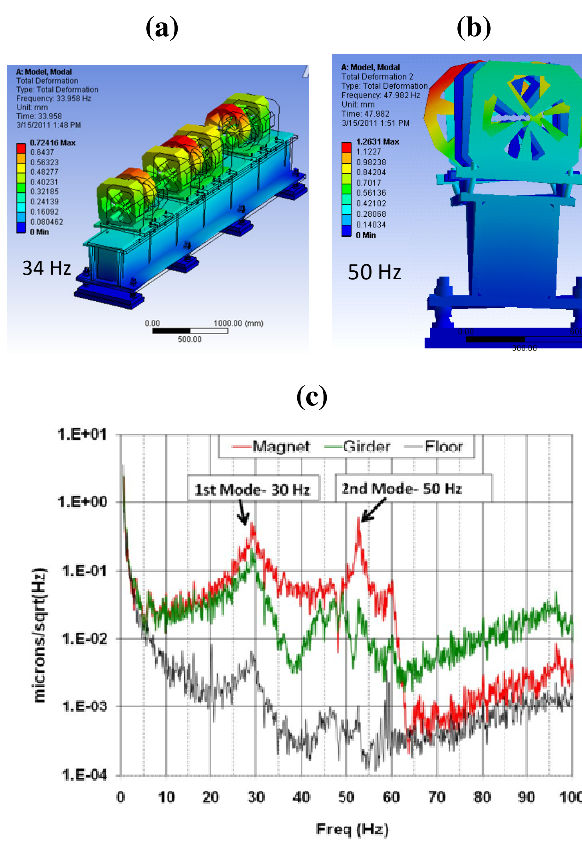


Figure 2: (a) 1st rocking mode of vibration, ~30 Hz, (b) - 2nd twist mode of vibration, ~50 Hz, (c) Vibration response of a girder-magnet assembly subjected to impact loading.

The ambient floor motion drops sharply with frequency (ω) as $1/\omega^4$. Random vibration tests conducted on the girder-magnet assembly (Fig. 3) confirmed that the amplification of the low-amplitude ambient motion in the high-frequency range (>30 Hz) had a negligible contribution to the total RMS (4-100 Hz) amplification in the vertical direction. Because of the rocking mode, the amplification in the horizontal direction is higher (1. 39 for magnets), but magnets' motion in the rocking mode is correlated. Moreover, the stability specification in the horizontal direction is 10 times less stringent.

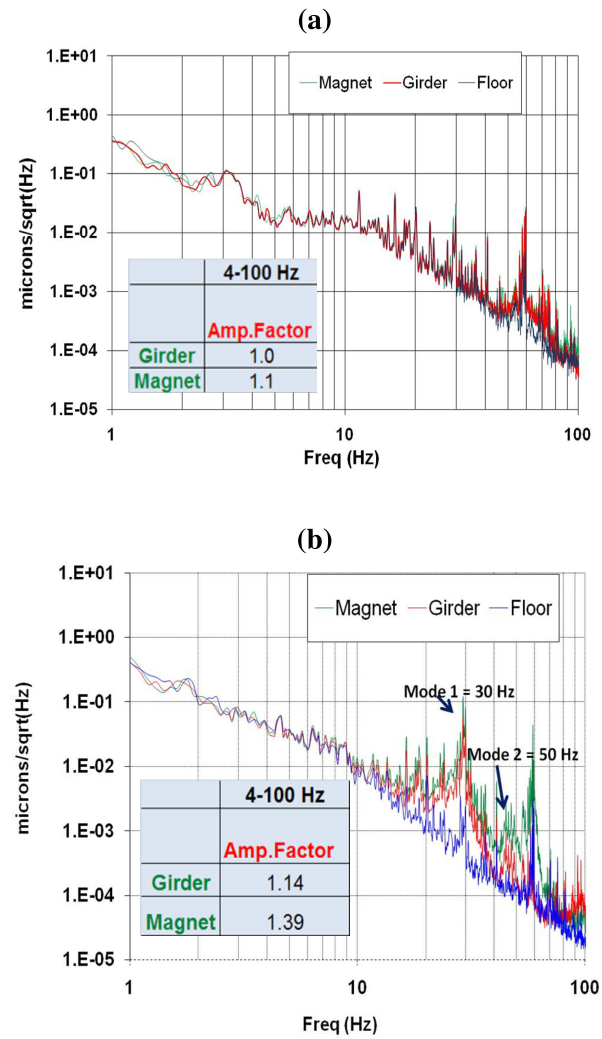


Figure 3: Random vibration tests: (a) Vertical √PSD, (b) Horizontal √PSD.

THERMAL FLUCTUATIONS

To ensure acceptable thermal stability of the storage ring magnets, process water and tunnel air temperature fluctuations will be maintained within ± 0.1 ºC. Both FEA (Finite Element Analysis) and test results confirmed that for a tunnel air temperature change of ± 0.1 °C with 1-hour time cycle, the girder (having large thermal mass) sees only ~1/10th of the ambient temperature change (Fig. 4a). FEA calculations showed that the resulting girder deflection will be ~22 nm (Fig. 4b). The magnet stability criterion (<25 nm) is met but essentially with no margin. However, the viscoelastic damping pads (discussed in the next section), introduced to counter the effect of diurnal floor motion, are expected to reduce the thermal bending of the girder by more than one order of magnitude.

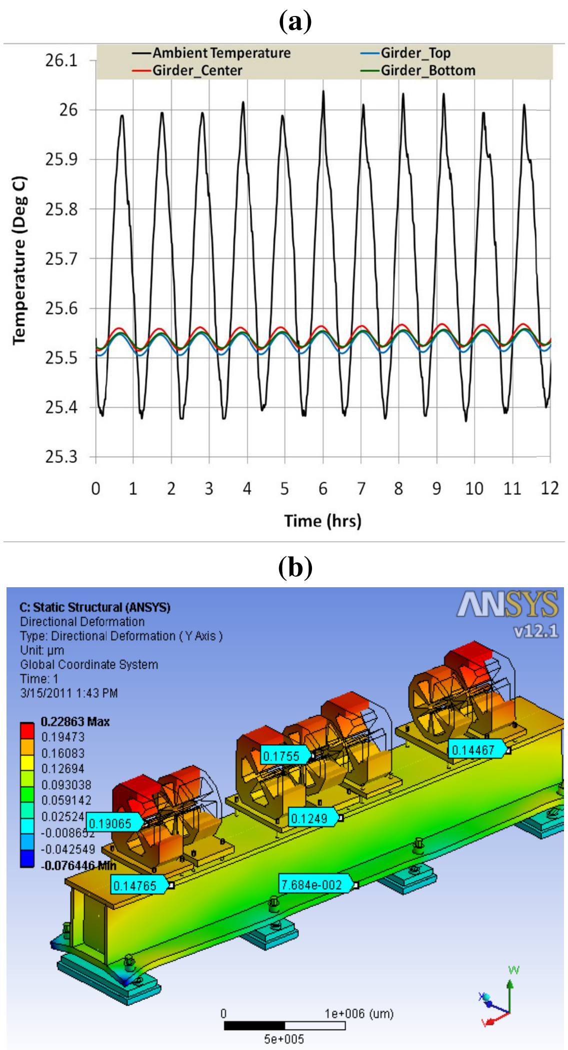
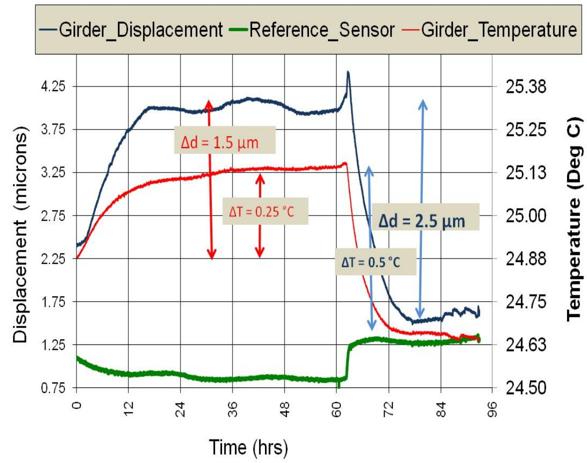


Figure 4: (a) Measured time-temperature girder response, ΔT_{Girder} = (1/10)ΔT_{Air}, (b) FEA girder deflection (deflection < 25 nm for ΔT_{Girder} ~ 0.01 °C).

To verify the accuracy of the FEA model we measured the absolute displacement (not deflection) on the bottom plate of the girder for a given temperature variation with a displacement sensor (SG-DVRT with a resolution of 15 nm) manufactured by Microstrain. The resolution of the DVRT was verified by measuring the displacement of a granite slab excited by an electro-magnetic shaker and then comparing the response with a calibrated PCB-accelerometer.

In Fig. 5 the absolute displacement measured on the bottom of the girder and girder temperature change are represented by the blue and red curve respectively. From the figure we can see that for a 1 °C change in the girder temperature, the absolute displacement change is 5-6 µm. The green curve represents the displacement of an Invar fixture which was used for holding the displacement sensors. The cumulative displacement (including the displacement of the Invar holder) of 60-70 nm for a girder temperature change of 0.01 °C is consistent with the FEA results (Displacement shown on the bottom plate of the girder in Fig. 4b).



1. Girder motion: ~6 µm/°C
2. Sensor holder motion: ~ 1 µm/°C
3. Total absolute displacement: 7 µm/°C

For a ΔT_{Girder} ~ 0.01 °C, absolute displacement = 70 nm

Figure 5: Absolute displacement measured on the bottom of the girder corresponding to a given steady state girder temperature change.

DIURNAL EFFECT

Synchrotron facilities such as the Photon Factory (Japan) [4] and SSRF (China) [5] have measured diurnal circumference variation as large as 1 µm/m. Floor temperature measurements at SSRF show that even though the tunnel floor temperature is stable to ± 0.02 °C, the experimental hall floor which sees larger temperature excursions can drag the tunnel floor (because of monolithic construction).

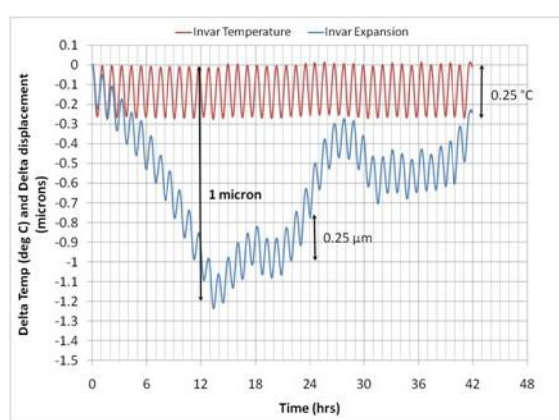
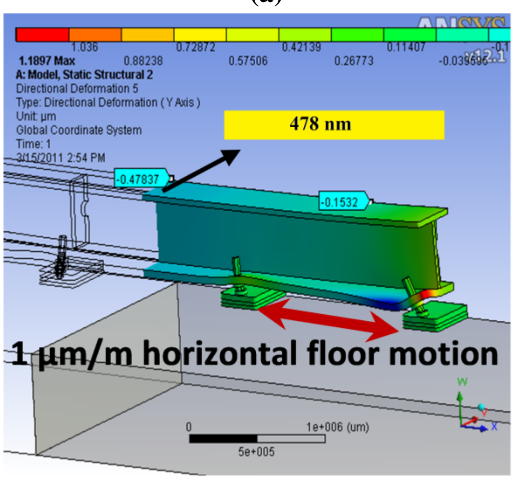


Figure 6: Displacement and temperature variation of an invar rod in a thermally stable environmental room.

Similar floor motion was detected in a test conducted in a temperature-controlled environmental room at Brookhaven National Laboratory. In this test, an Invar rod of ~ 1 m length was installed with one end clamped and a displacement sensor mounted at the other free end of the rod, to measure the horizontal expansion. The air temperature in the environmental room was cycled between ± 0.3 °C with one hour time cycle. Temperature sensors were mounted on the invar rod (red curve in Fig.6) which showed a temperature fluctuation of ~0.25 °C. The displacement reading measured on the Invar rod showed two distinct components (blue curve in Fig. 6): an amplitude ~ 0.25 µm (1-hour cycle) which is consistent with the CTE of invar (1µm/m/°C) for a temperature fluctuation of 0.25 °C, and an amplitude of ~1 µm with 12-hour cycle, which clearly is related to the day-night temperature variation.

Analyses results show that the stiff and over-constrained (grouted interface between the girder floor plate and the concrete floor) girder resists the longitudinal floor motion (1 µm/m) by bending-type deformations, resulting in a relative vertical deflection, ~300 nm over the effective length of the girder (maximum distance between the center and end-magnet on the girder) (Fig. 7).

(a)



(b)

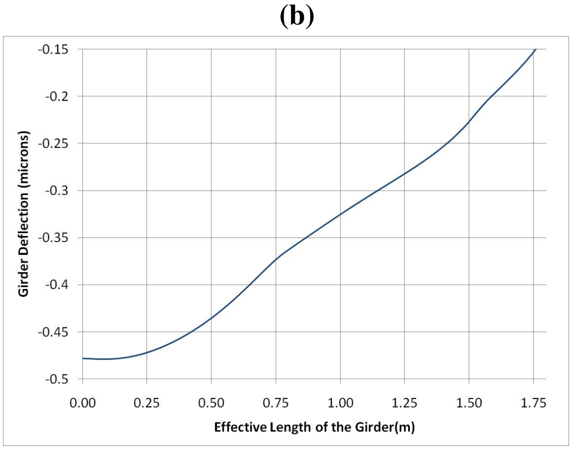
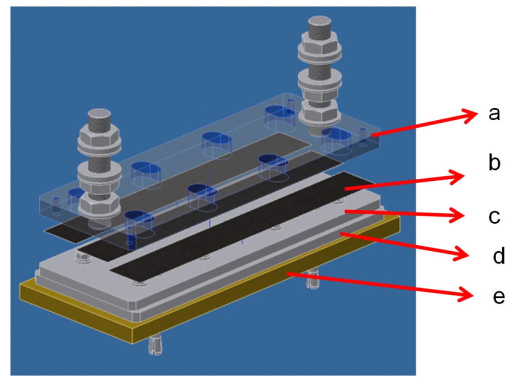


Figure 7: (a) FEA results - girder deflection due to diurnal floor expansion, (b) Girder deflection over the effective girder length.

To relax the over-constrained condition without losing vibration stability we evaluated the concept of making the mounting pad of the girder as a viscoelastic sandwich with thick top and bottom steel plates (Fig. 8a). The intermediate adhesive film of viscoelastic material (3M^{TM}) allows relative displacement between the plates to absorb the slow diurnal floor motion without causing the girder to deform (Fig. 8b). Vibration tests done on this configuration showed a slight reduction in the horizontal amplification factor as well because of the vibration damping property of the viscoelastic material.

(a)



(a) 1.5" top plate, (b) 0.01" viscoelastic pad, (c) 1" steel bottom plate , (d) 1" grouted steel plate, (e) grout.

(b)

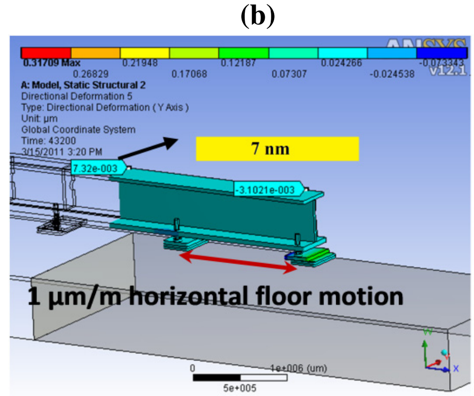


Figure 8: (a) Girder mounting base design incorporating the viscoelastic material, (b) FEA vertical deflection of girder with the viscoelastic pad.

Tests were conducted in a temperature-controlled environmental room to test that the viscoelastic pads allowed free relative motion between the floor and the girder. Displacement sensors were mounted at locations A and B which are at a distance of 3 and 1.5 m from the center of the girder, respectively (Fig. 9). The mounting frame of the displacement sensor was fixed to the grouted part of the girder mounting base and the measuring head of the displacement sensor was in contact with the top movable plate, thus measuring the relative motion between the floor and the girder.

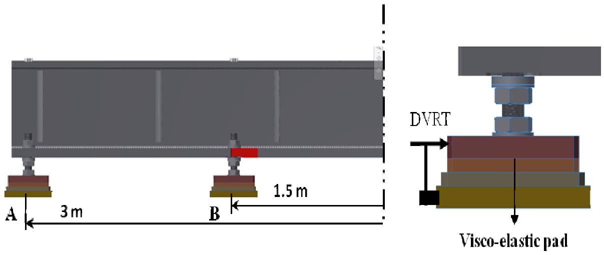


Figure 9: Thermal-testing scheme for the girder with viscoelastic pads.

The temperature of the room was cycled between ± 0.3 °C with 1-hour cycle which resulted in an average temperature variation of ± 0.025 °C (1/10th of the ambient) in the girder (Fig. 10a). Fig. 10b shows the displacement readings for the locations A (blue curve) and B (red curve) explained above. The displacement plot clearly shows the following two cyclic components; there is a 1-hour cycle, with displacement amplitude that is consistent with the CTE of 11 μm/m/°C for steel, and a girder temperature change of ~ 0.025 °C. The 12-hour displacement amplitude, which is 3-4 times larger than the 1-hour amplitude, is clearly the floor motion relative to the girder. Also, since the distance of point A is twice that of point B, the displacements measured at these two locations scale approximately by a factor of 2.

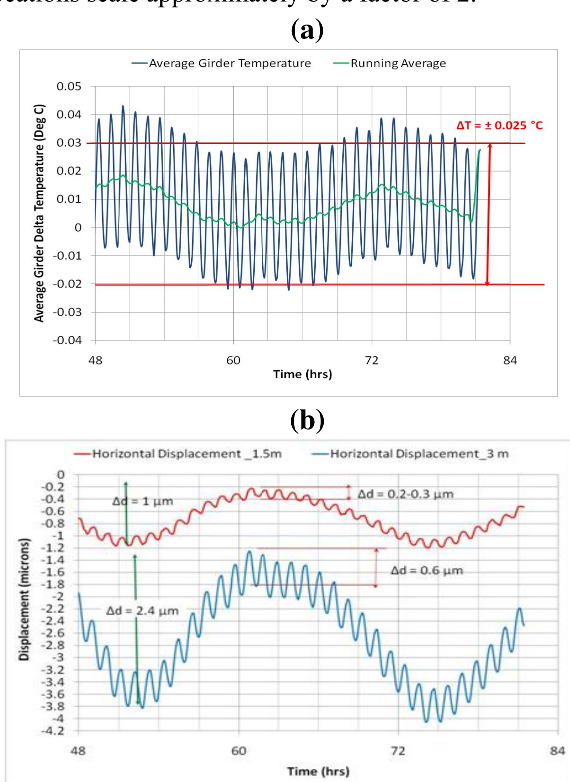


Figure 10: (a) Girder temperature variation, (b) Relative horizontal displacement between the girder and the floor.

CONCLUSIONS

The NSLS-II girder support system has been designed to be stiff and over-constrained to prevent amplification of the ambient floor vibration. The adverse effect of over-constraining on thermal stability is countered by viscoelastic pads which prevent thermal bending deformations for both the tunnel temperature fluctuations and the diurnal floor expansion. The stringent magnet stability specifications are thus met by optimizing the stiffness of the girder support system with the flexibility of its viscoelastic constraints.

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