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MEASUREMENTS AND COMPUTER SIMULATIONS OF THE EFFECT OF MAGNET VIBRATIONS ON THE ELECTRON BEAM ORBIT IN THE NSLS-II STORAGE RING

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Abstract

One major factor contributing to electron beam stability in a storage ring is the mechanical vibrations of magnets. At NSLS-II, we use speakers to induce controlled vibrations in one of the support girder of the magnets. Beam position monitors (BPM) distributed around the storage ring measure the spatial distribution of beam oscillations. Collected accelerometer data is used to create and validate a computer model through a MATLAB-based simulated commissioning tool. This ongoing work is essential for refining our simulation models and experimental approaches, ultimately aiming to enhance beam stability through improved vibration suppression techniques.

INTRODUCTION

The next-generation synchrotron light sources aim to provide X-ray beams with extremely high brightness for a wide range of applied research. These applications demand ultra-high resolution, imposing tight electron beam stability specifications [1]. Thus, stability of the electron beam is one of the most important properties to achieve brilliant X-ray beams. Achieving such stability demands an analysis of the impact of any possible sources of beam disturbance, such as ground vibrations, thermal effects, and power supply noise.

This study investigates the impact of controlled magnet vibrations on the electron beam orbit at NSLS-II. Our ultimate goal is to determine whether this setup is effective for the concept of ground vibration cancellation to preserve high brightness of the beam at NSLS-II. We used speakers mounted on a girder to induce the first (roll mode) at 30 Hz [2] and second (yaw mode) at 49 Hz fundamental modes of the girder-magnet assembly at NSLS-II, monitoring the beam's response via BPMs. Furthermore, a computational model was developed using the Simulated Commissioning Tool [3], enabling the simulation of the beam orbit's response to these vibrations. The constructed model allows us to analyze the impact of magnet vibrations on electron beam motion in an isolated environment, thus avoiding other contributions to beam motion. This paper details our approach in developing and validating the model, addresses the challenges faced, and proposes future directions.

In the following sections, we will demonstrate the experimental setup, describe the computational model, and present a comparison between simulations and measurements, followed by the conclusion.

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EXPERIMENTAL SET-UP

Figure 1 shows the schematic of our experimental setup. In this setup, two Dayton Audio BST-300EX shakers are installed at the upstream and downstream ends of Girder 4 in Cell 13 (C13G4) at NSLS-II. The setup is equipped with 12 PCB-393B31 accelerometer sensors, positioned on the quadrupole magnets, speakers, girder, and the ground. Using a dual DDS channel signal generator and a QSC RMX 1450 dual-channel amplifier, the speakers are powered to shake the girder at various frequencies both in phase and out of phase. The data from these accelerometers are numerically integrated over the frequency range of 2 to 100 Hz to obtain the power spectral densities (PSD) of the displacement signals and RMS displacements. This frequency range is chosen to align with the relevant frequency range of ground motion. Above 100 Hz, the amplitude of ground motion becomes negligible [4], and such motion is no longer a concern for electron beam stability purposes. As the speakers are excited, 10 kHz fast acquisition (FA) data is obtained from the BPM in the control room. This data is collected for ten seconds to ensure the capture of the impact of the magnet vibrations. It is used for comparison with the simulations.

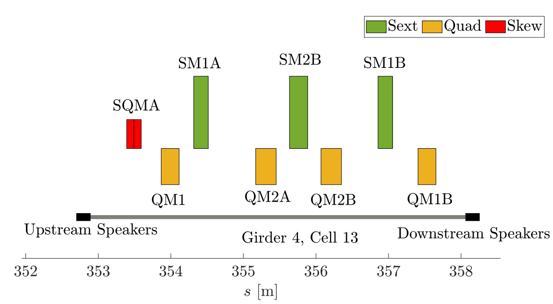

Figure 1: Schematic representation of girder C13G4 and its quadrupole and sextupole magnets, along with the speaker locations.

COMPUTATIONAL MODEL

In our study, we utilized the Toolkit for Simulated Commissioning (SC), a MATLAB-based package that extends the capabilities of the Accelerator Toolbox (AT) [5]. SC is specifically designed to perform precise commissioning simulations for storage rings. It introduces advanced error handling, allowing for the straightforward implementation of dynamic errors such as magnet vibrations. We modified two functions native to SC, customizing the package for this experiment:

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- **SCapplyErrors** is modified to use the given magnet displacement values as amplitudes of a sinusoidally varying offset:

$$x = a_{\text{rms}} \sin\left(2\pi f_{\text{vib}} nT + \phi\right)$$

  Here, x represents the magnet offset after n turns, a_{rms} is the RMS displacement of the magnet, f_{vib} is the vibrational frequency, T is the period of a single turn, and ϕ is the phase between the speakers.

- **SCgetBPMreading** was modified to save the electron beam trajectory at each turn. This is then used as the starting point for the next turn, an essential step in studying the impact of dynamic errors.

An initial trajectory, obtained using one of the findorbit AT functions, represents the pre-vibration state of the electron beam. We perform turn-by-turn tracking, updating magnet offsets at set intervals. Convergence studies confirmed that the amplitude change of the electron beam motion is negligible for update intervals between 1 and 100 turns.

A standard synchronous detection technique is used for the BPM data processing, the goal of which is to extract the amplitude of the measured sine-wave BPM signals as discussed in Ref. [6]. This involved comparing our simulated BPM readings with experimental BPM FA data.

RESULTS

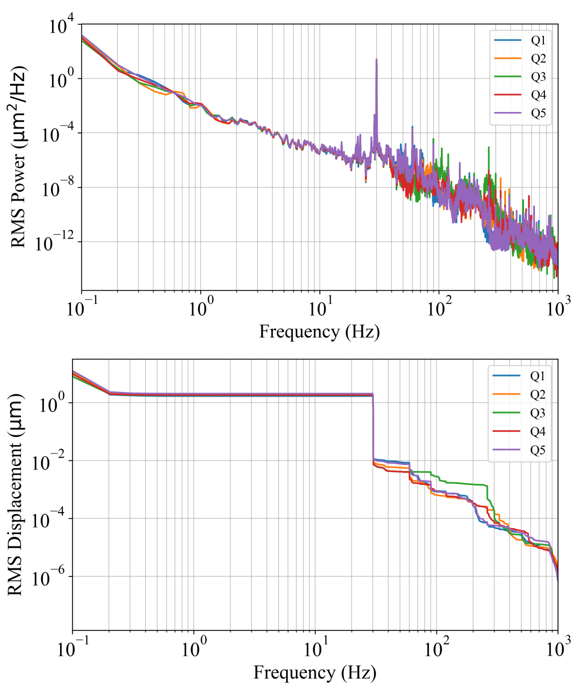

Figure 2: A PSD and RMS displacement of magnets as a function of frequency for the in-phase induced signal at 30 Hz.

In this study, we induced measurable vibrations in the girder-magnet assembly by transmitting signals at specific frequencies through speakers mounted both upstream and downstream. These speakers were excited in both in-phase and out-of-phase configurations.

We established that for the NSLS-II girder-magnet assembly, the first fundamental mode of vibration has a natural frequency of approximately 30 Hz, wherein all the magnets move in phase. Figure 2 shows the PSD of the twice-integrated acceleration data, which displays prominent peaks at 30 Hz, and the RMS displacements of the magnets as a function of frequency.

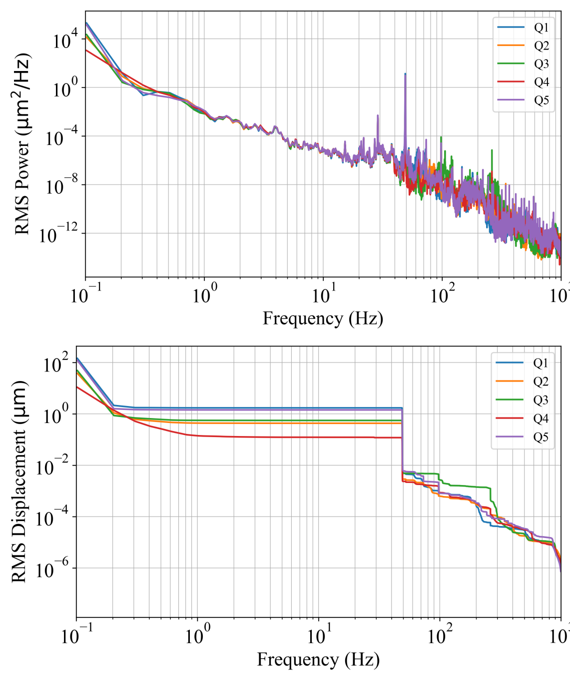

Figure 3: A PSD and RMS displacement of magnets as a function of frequency for the out-of-phase induced signal at 49 Hz.

The second fundamental mode occurs at 49 Hz, which is induced when the speakers are excited out-of-phase, causing the magnets to move out of phase. Figure 3 shows the PSD of the twice-integrated acceleration data, which features prominent peaks at 49 Hz, along with the RMS displacements of the magnets as a function of frequency.

The large magnet displacements induced by the vibrations result in electron orbit distortion, which we simulated and measured using BPMs. Figure 4 shows the orbit distortion model (in blue) and measurements (in orange) for speakers excited at 30 Hz and 49 Hz, both in-phase and out-of-phase. As expected, the amplitude of the in-phase motion is higher than that of the out-of-phase motion. The computational model shows good agreement in some cases and a slight discrepancy in others. Approximations in the computational model, such as assuming single-frequency magnet oscillations and neglecting errors other than induced vibrations, may contribute to these discrepancies. Additionally, we have five sensors on the magnet, and for other magnets, we take the average from adjacent magnets.

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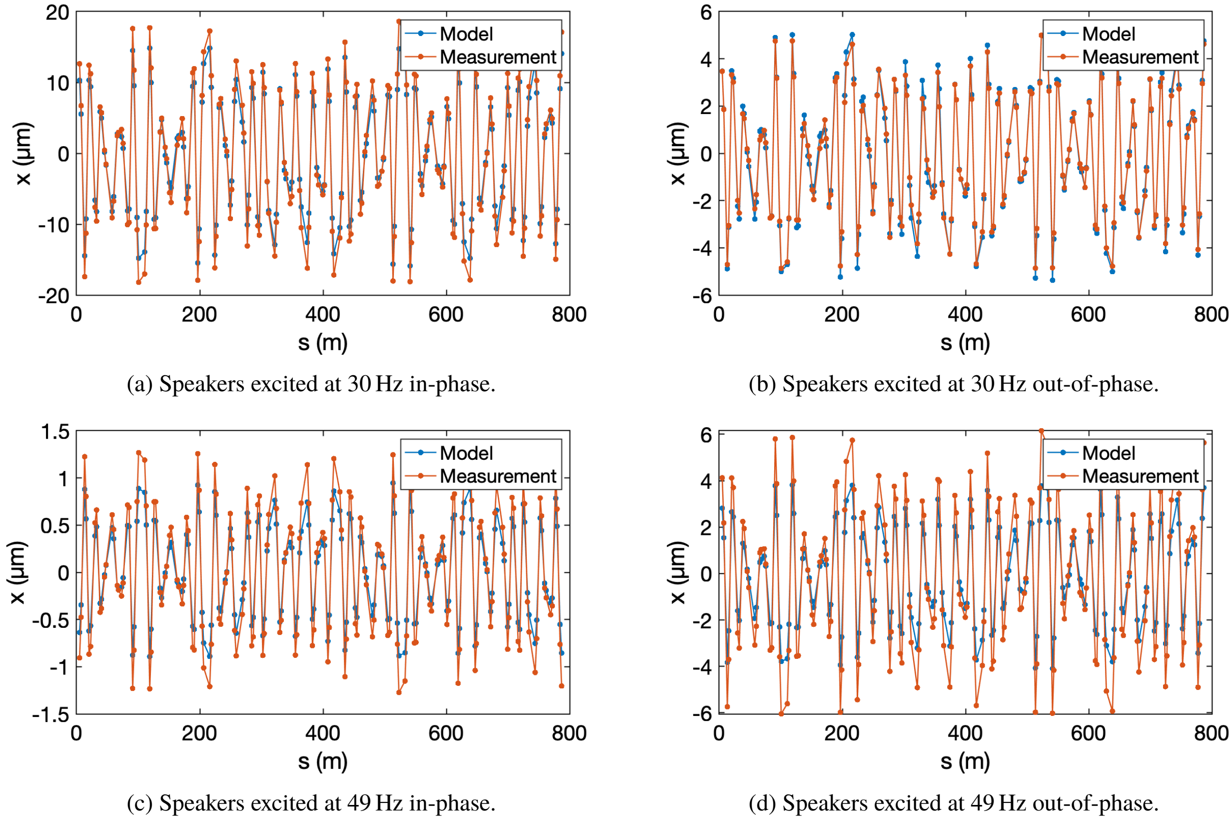

(a) Speakers excited at 30 Hz in-phase.

(b) Speakers excited at 30 Hz out-of-phase.

(c) Speakers excited at 49 Hz in-phase.

(d) Speakers excited at 49 Hz out-of-phase.

Figure 4: Comparisons of AC orbits obtained from the computational model and from the BPM FA data.

In the future, we will also test the BPM resolution with different amplitudes of vibration by changing the power. Previously, we had issues with this test as the speaker burned out at high power. We now have a different amplifier, and the speakers are better glued to the girder. Overall, this study strengthens our confidence to further test this setup for a better understanding of the correlated and uncontrolled motion of magnets for the active suppression of vibration.

CONCLUSION

This study investigated the impact of controlled vibrations on electron beam motion in NSLS-II by utilizing speakers mounted on one of the magnet support girders. One significant finding is that inexpensive, low-power (~ 50 W) audio speakers are sufficient as a counteractive vibration source, achieving approximately 100 nm rms. Through dynamic simulations conducted with the Toolkit for Simulated Commissioning and the Accelerator Toolbox, complemented by accelerometer data, we enhanced our understanding of magnet displacement and the resulting orbit motion. These findings contribute to our ongoing efforts to optimize the low-emittance upgrade of NSLS-II by providing actionable insights into the mechanical stability and precision of the storage ring's support structures.

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