ISBN: 978-3-95450-229-5 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2020-MOPB13

AUTOMATED MECHANICAL INSPECTION AND CALIBRATION OF INSERTION DEVICES IN APS STORAGE RING*

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Abstract

A novel technique has been developed to automatically inspect and calibrate the 53 permanent magnet insertion devices in the Advanced Photon Source (APS) storage ring. This technique employs standard frequency domain analysis to create easily identifiable signatures in an actionable format. We will discuss the mechanisms and actions taken behind various observed trends and its application for continuous monitoring and predictive maintenance of these devices. This technique has enabled predictive maintenance and provided new insights into optimizing device performance.

INTRODUCTION

Hybrid permanent magnet undulator (HPMU) insertion devices require reliable micron level accuracy and precision during operation [1]. Many of the devices have been in service for more than 25 years. Each of these devices have four or more drivetrains totalling to over 212 in operation. The continuous operation and radiation environment of the APS storage ring presents unique challenges for maintenance. To ensure the reliability of devices, manual measurements at common points of operation and regular preventative maintenance are performed during the available triannual "shutdowns". While this provides a sanity check and adheres to manufacturers' recommended maintenance schedule, it does not effectively prevent or provide insight to commonly occurring issues during operation. To enable a more efficient, comprehensive, and data-driven solution, a program to perform automated inspections was written.

Positioning of the upper and lower magnetic support structures (strongbacks) are each controlled by two individual drivetrains. Though they are controlled and operated individually, each of these two drivetrains are coupled through their shared connections with the upper or lower strongback. This coupling action can lead to a constructive amplification of errors in each drivetrain. Additionally, the drivetrain and feedback systems are inset from the end of the strongback. Small angular changes in the orientation of the strongback due to small errors in the drivetrain system will be magnified over the length of the strongback, leading to larger uncertainty in the exact position of the ends of the magnetic structures. These magnification effects make it crucial to identify and eliminate preventable errors in the drivetrain.

* This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility at Argonne National Laboratory and is based on research supported by the U.S. DOE Office of Science-Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
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The most common faults during operations in order of occurrence is overtravel limit trip, extreme limit trip, motor stall, linear encoder failure, and rotary encoder failure. The overtravel switches are often set within 100 µm of the usable gap to balance machine safety and user reliability. Given that these switches are located at the ends of the strongback, the mechanical inaccuracies present are significantly amplified. Without quantitative characterization, reasons for the fault are difficult to troubleshoot due to the initial switch setting, start of travel position, and travel end positions all being factors in the diagnosis. The other faults can be equally difficult to diagnose due to the mechanical, electrical, and software components involved.

METHOD

Each HPMU contains a redundant set of feedback devices meant to maintain operation in case one fails; a rotary encoder directly coupled to the motor and a linear encoder directly coupled between the static frame and strongback. The rotary encoder uses a hard coded relationship between turns of the motor and physical position of the strongback to extrapolate its position. The linear encoder directly measures the position of the strongback. Errors in the drivetrain system (Fig. 1) that controls the strongback will therefore present themselves as an accumulated discrepancy between the rotary feedback and linear feedback. By analysing the discrepancy as a function of actual gap, a complete characterization of the drivetrain and crosschecking between the encoders can occur.

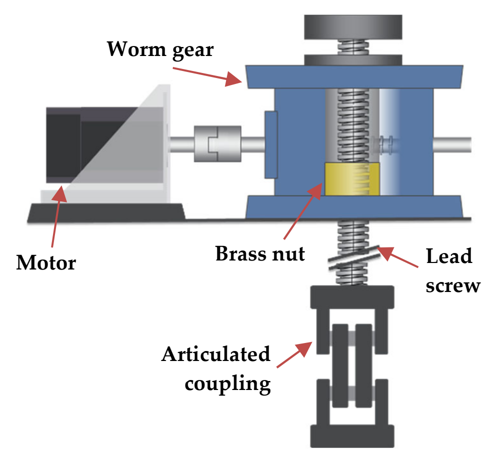

Figure 1: The drivetrain of an APS undulator device consists of a motor coupled to a 60:1 worm gear assembly. Motion is transferred to a lead screw, which is threaded through a bronze nut and connected directly to the strongback via an articulating coupling.

A python script sequentially commands each of the 53 insertion devices installed in the APS storage ring to move at a slow speed while oversampling the position readback

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from each encoder. These data are collected using EPICS and device specific information needed for data processing is pulled from the Component Database (CDB) [2]. The oversampled position data from the rotary and linear encoders are subtracted from each other. Any mismatch due to the non-synchronicity of the data collection is accounted for by interpolation. The plot shown in Fig. 2 is then generated.

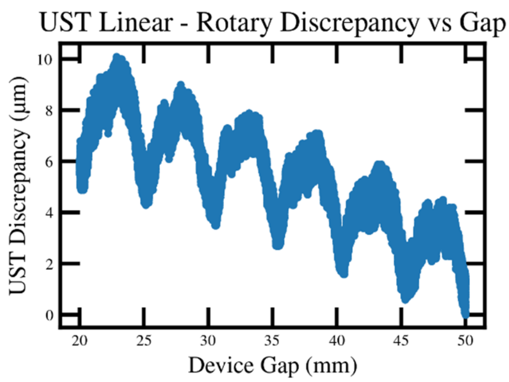

Figure 2: The discrepancy between linear and rotary encoder gap readings can illustrate mechanical error or defects in the system. Here, a repeating curve with a period of ~5 mm and an amplitude of ~6 µm.

The plot in Fig. 2 contains valuable information both at the 1 mm scale and the 1−10 µm scale. A standard fast Fourier transform (FFT) and power spectral density (PSD) analysis is performed to identify and extract meaningful signals in the discrepancy data shown in Fig. 3. Special attention is given to the frequencies that correspond to the characteristic periodicities of certain components in the drivetrain known to affect the accuracy of the positioning system. Table 1 lists the components in question along with their expected contribution to the accumulated drivetrain error when they are manufactured and installed within predefined tolerances.

Table 1: Expected contribution and repetition cycle of various drivetrain components based on manufacturing and installation tolerances.

Component	Repetition Distance µm]	Amplitude [µm]
Rotary Feedback	84.67	<< 1
Motor Coupling	84.67	< 1
Worm Drive	5080	< 3
Leadscrew / Nut	5080	< 4
Linear Encoder SDE	64	< 4

One revolution of the components positioned before the worm gear corresponds to 1/60 of a revolution of the leadscrew. The magnitude of their expected errors should then be reduced by a factor of 60, making them a negligible contribution to the total error. Spectral analysis, therefore, concentrates on the frequencies 1/5080 µm^{-1} and 1/64 µm^{-1} and their related harmonics.

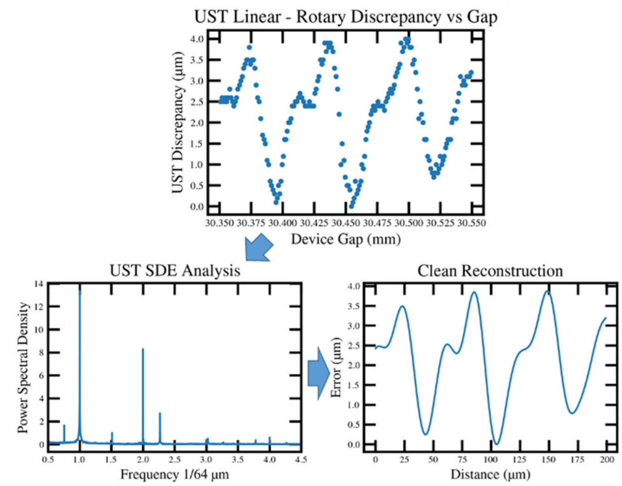

Figure 3: Frequency domain analysis can extract meaningful signals from the data and give information about the behaviour of components in the system. Signals can then be reconstructed from spectral information leading to a cleaned version of the original data. This cleaned data/fit can then be used for acceptance criteria and can automated acceptance testing. The plots shown are specifically looking at the SDE of the linear encoder which occurs every 64 µm.

The generated plots are consolidated on an easy to review report generated in HTML for each of the 53 devices. The use of HTML enables the ability for it to be hosted for others to view and makes it more intuitive to navigate. A summary is also included on the report of the settings used during data collection.

RESULTS

Over the past year this technique has enabled the finding of the following otherwise undetected issues: six devices with worn-out compensation springs, four preliminary rotary encoder failures, four linear encoder failures, and over 10 encoder alignment/tuning errors. Most importantly it provided a baseline expectation of dynamic device performance. This baseline led to quick pinpointing of mechanical errors in each device which has provided critical time savings for minimizing onsite personnel during the COVID-19 pandemic. In addition, it provided a baseline of comparison for the new construction of devices for APS-U catching manufacturing/assembly errors. Figure 4 shows two of the detected issues mentioned above.

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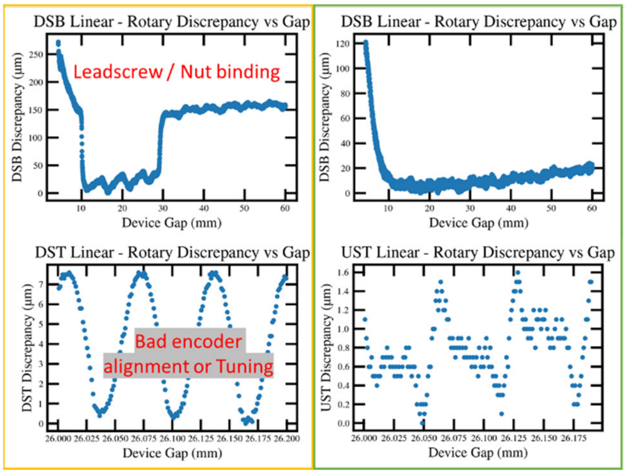

Figure 4: Plots on the left show devices out of tolerance with the cause in red. Plots on the right are for reference of what they should look like.

FUTURE WORK

Further improvements can be made by incorporating machine learning for anomaly detection and automatically classifying common defects. A more user-friendly version is currently in the works for use in other areas in the APS where insertion devices are being worked on. In addition, it is planned to incorporate the auto-calibration of linear encoders into APSU ID motion control system to provide better gap accuracy for the users.

CONCLUSION

A new technique to better monitor and provide insight to the insertion devices installed in the APS storage ring has been developed and successfully tested. This technique has provided great value to operations enabling predictive maintenance and improved insight to device performance. This has been of great value during the COVID-19 pandemic as this enabled devices to be more efficiently diagnosed and be comprehensibly monitored remotely.

ACKNOWLEDGEMENTS

This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility at Argonne National Laboratory and is based on research supported by the U.S. DOE Office of Science-Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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