UPGRADE OF THE EUROPEAN XFEL PHASE SHIFTERS

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Abstract

To eliminate the impact of radiation shower on the incremental encoder readout and provide a better dynamic movement the upgrade of all phase shifters of the European XFEL have been successfully done without interruption of the operation schedule. The implementation steps, as well as the results of the hardware and software tests made in the laboratory, are presented. The sensitivity of the Renishaw RGH22O15D00A encoder to the radiation shower was measured in the SASE3 undulator system, and the results are presented.

INTRODUCTION

At the European XFEL undulator systems 88 gap variable phase shifters are in use [1]. They had been equipped with the "Oriental Motor" stepping motors and "Renishaw" linear incremental encoders. To bring the phase shifters into the operational state, the homing procedure was required for the linear incremental encoder. During the operation in the tunnel under the beam condition, at some undefined state, the counts of the encoder have been randomly lost. This effect has not been observed during the tests performed in lab. To bring then phase shifters back into the operational state, the rehoming procedure must have been done, which was breaking the operational routine. Additionally, in the coupled mode [1] at the small undulator gaps the phase shifters have been stuck during the movement because of the speed limitation of the stepping motor.

Based on the experience, gained during the first operation of the phase shifters in the tunnel, the decision has been made to build a test setup using the Beckhoff servomotor with the integrated absolute rotary encoder instead of the old stepping motor to create a solution, which will avoid future operational difficulties of the upgraded phase shifters.

HARDWARE UPGRADE

For the phase shifter upgrade the following main steps were performed:

- Exchange of the motor with the bearing
- Upgrade of the intersection control rack (ICR)[1]
- Integration of the servo axis in the undulator local control system [1]

The ICR has been modified in order to operate the phase shifter with the "AM8122-0F21-0000" servomotor instead of the old stepping motor. The following hardware components have been uninstalled from the ordinary ICR during the upgrade.

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Although the servomotor is equipped with the integrated absolute rotary encoder, which is an indirect gap measurement system, the functionality of the existing feedback system based on the incremental linear encoder has been retained and used as a reference direct gap measurement system, to be able to make the initial calibration of the indirect gap measurement system. All related hardware and connections remained identical to the ordinary ICR.

The following hardware components have been installed during the ICR modification:

- EL 7211-0010 PLC servomotor terminal
- PULS CP10.481 DIN rail power supply
- Cable from the ICR to the servomotor

All stepping motor control related hardware was preliminary deinstalled from the ICR:

- EL 2521-0024 PLC pulse train terminal
- EL 2004 PLC digital output terminal
- RKD514LMC, stepping motor driver
- Terminal units
- Cable from the ICR to the stepping motor
- Corresponding wiring

SOFTWARE UPGRADE

The servo axis has been implemented in the system manager configuration instead of the stepping motor axis in order to operate the upgraded phase shifter. To keep the functionality of the existing linear encoder as a direct gap reading system one more special type of axis has been created named "Linear Encoder". This axis is not involved in the motion system and was only used later as a reference direct gap measurement feedback system for the correction curve calculation.

Before replacing the stepping motor with servomotor the scaling factor has been calculated, set in the system manager and the servomotor has been driven to the 40 mm, which is the half of the 80 mm previously set phase shifter gap. Due to the specific mechanic of the phase shifter, the value of the absolute rotary encoder in the servomotor corresponds to the double value of the linear encoder. Once they have been equated to each other, the motor has been replaced together with the flange and the coupling. The appeared mismatch between two feedback systems after motor replacement has been compensated by position bias value. The linear encoder value has been also corrected by position bias value to the 80 mm.

Calculation of the Scaling Factor

The scaling factor (SF) is a crucial parameter for the positioning accuracy. The value of the scaling factor has been calculated by using the formula specified below. The num-

ber of single-turn bits is taken into account in the calculation of the scaling factor. The default setting of the EL 7211-0010 servomotor terminal is 20 single-turn bits. This value is also used for calculating the scaling factor.

$$SF = \frac{D}{2^{SB}} = \frac{360^\circ}{2^{20}} = 3{,}43322753906 \times 10^{-4} \quad (1)$$

where:

D – Distance/Round, SB – Singleturn Bits

For the final calculation of the SF the mechanics of the PS need to be taken into the account, in particular, the reduction coefficient of the gearbox as well as the pitch of the double direction ball screw spindle. The following formula needs to be used for the calculation:

$$PS_{SF} = \frac{SF}{I} \times \left(\frac{360}{P}\right) = \frac{3{,}43322753906 \times 10^{-4}}{3600} = 9{,}536743164055556 \times 10^{-8} \quad (2)$$

where:

I (Gearbox Reduction Coefficient) = 50

P (Pitch) =5 (5mm/360° of the phase shifter's spindle)

The calculated PS_SF is universal for all phase shifters and will be used later during the phase shifters upgrade campaign.

FIRST OPERATION OF THE UPGRADED PHASE SHIFTERS, MEASUREMENT RESULTS

Gap Dependent Deformation

Due to the gap dependent magnetic force which appears between upper and lower girders of the phase shifter, the frame is experiencing also corresponding gap dependent deformation. So called gap dependent correction coefficients have to be calculated and taken into the account because of the indirect gap measurement system, which is involved in the operation of the upgraded phase shifter. The special software called Correction Coefficient Calculator (CCC) has been developed to operate the phase shifter automatically depending on the configuration file in which the sequence of the gap values, speed of the movement and the number of iterations can be specified [2]. Depending on the content of the configuration file, the output file is created. The reason of this activity to measure the gap dependent deformation by comparison of the direct and indirect gap measurement system values. The resolution of the set gap values depends on the gap region. For instance, starting from the 30 mm gap downwards, where frame deformation forces are highly increasing, the scanning has been done with 0.5 mm steps to increase the number of data points and as a result the accuracy of the obtained data. The data have been analyzed and the gap dependent lookup table has been created, which later was implemented in the PLC project as a correction table for the rotary encoder. In the Fig 1 shown the subtraction of the rotary and linear encoders values as a function of the set gap.

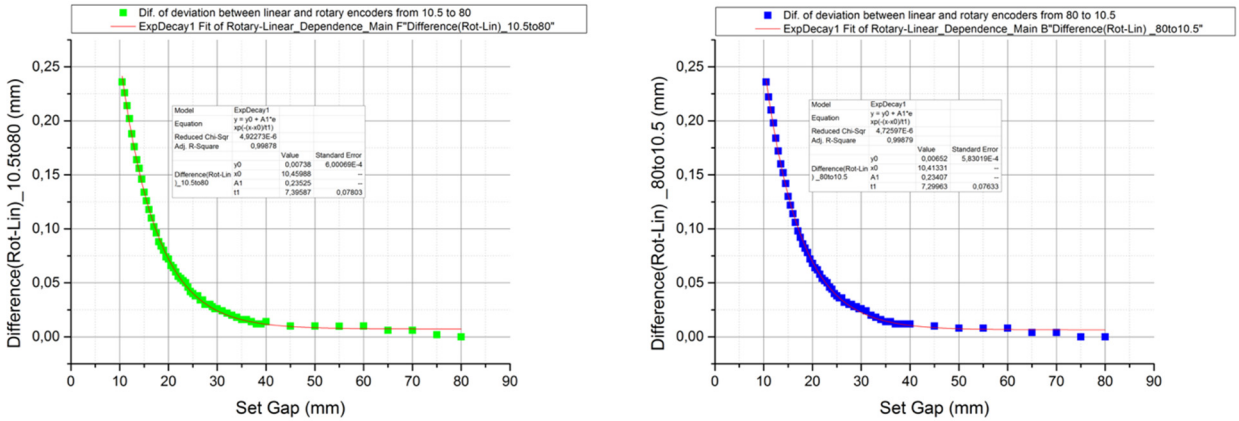

Figure 1: The difference of the rotary and linear encoders values as a function of the set gap. The left plot shows the dependency on gap increase scan mode, right on gap decrease scan mode.

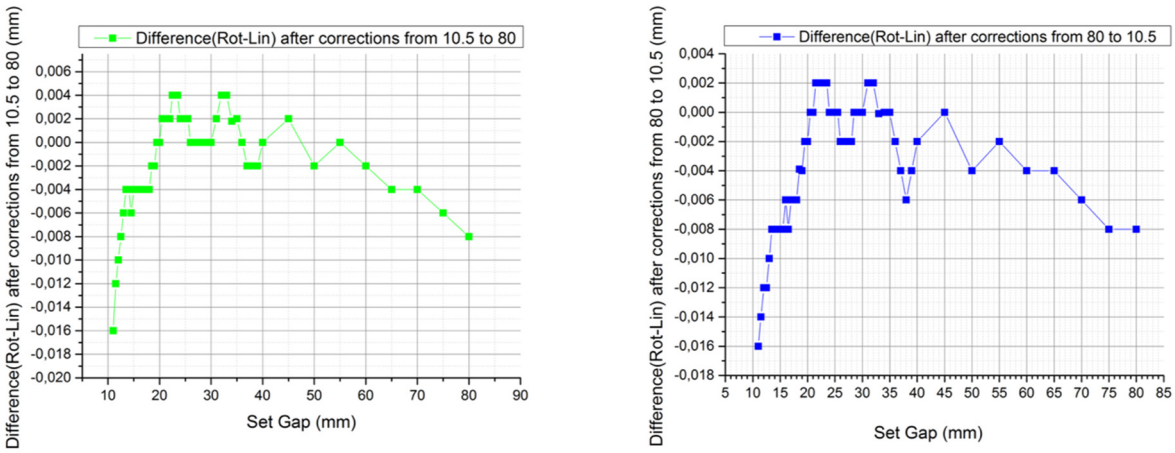

Figure 2: The difference of the rotary and linear encoders values as a function of the set gap after applying the correction coefficients. The left plot shows the dependency on gap increase scan mode, right on gap decrease scan mode.

After implementation of the correction coefficient curve in the PLC project, the same measurements have been performed. The results are presented in Fig. 2.

As can be seen in the present plots, the maximum deviation is equal to 16 µm which is an acceptable value for indirect gap measurement system.

Hysteresis Study

After the implementation of the correction coefficients the study of the upgraded phase shifter gap positioning accuracy and reproducibility has been done. This study has been performed in order to investigate the gap positioning accuracy by operating the phase shifter with indirect gap measurement system, namely absolute rotary encoder. In order to measure the actual hysteresis, the same CCC software have been used. The only difference was the scanning has been done first downwards from 80 mm till 10.5 mm gap and then backwards to 80 mm in one scan. The plots in the Fig. 3 are illustrating the scanning results. The maximum of 4 µm deviation has been detected and considered as a hysteresis.

Coupled Mode

To be able to operate the phase shifter and especially study the phase shifter behavior in so called coupled mode, the dummy undulator has been developed based on four undulator servomotors and two linear encoders, and the PLC project has been adopted to the created setup. Coupled mode is a special mode in which the phase shifter is operated as a slave of the undulator and the gap value is set as a function of the undulator gap. In this mode the phase shifter has to follow the undulator in case of any gap change.

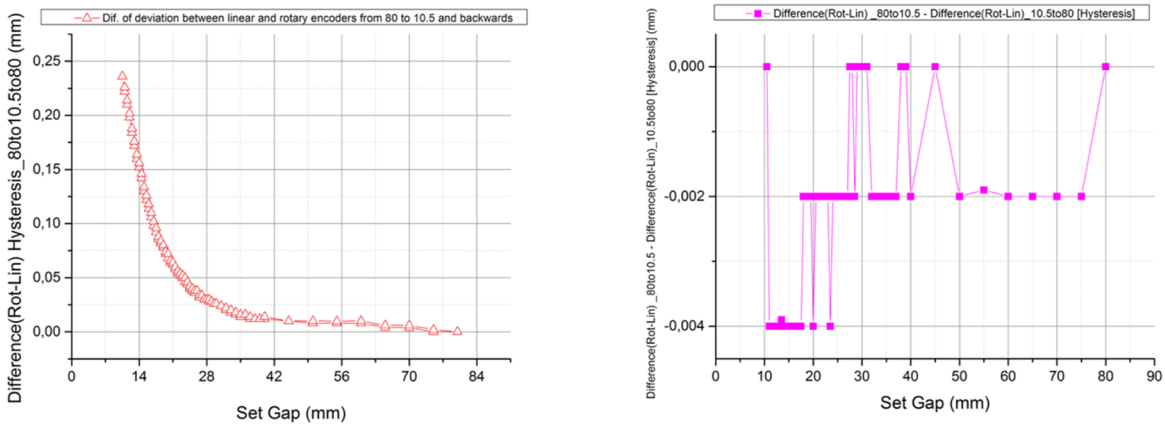

Figure 3: The left plot shows the difference of the rotary and linear encoders values as a function of the set gap after applying the correction coefficients in downwards and backwards scanning mode. The right plot shows the difference of two curves presented on the left plot.

The following signals have been tracked by Scope View to study the mentioned scenario:

Und_LT_Actual Pos*2	Left Top axis rotary encoder position*2
PS_Rotary Encoder*2	Phase shifter rotary encoder position *2
Lag Distance	Lag distance value

The dummy undulator has been obviously operated in the “Rotary Encoder” mode. Since the rotary encoders are

giving the calculated value of the half of the gap either for the undulator or the phase shifter, the values have been multiplied by a factor of two. A set of measurements has been performed to study the reproducibility of the phase shifter gap positioning, the lag distance between the undulator and phase shifter actual gap value using different speed in coupled mode. The Scope View screenshot as an example of the described study is shown in Fig. 4. The measurements have been performed with 0.1% of undulator gap speed movement.

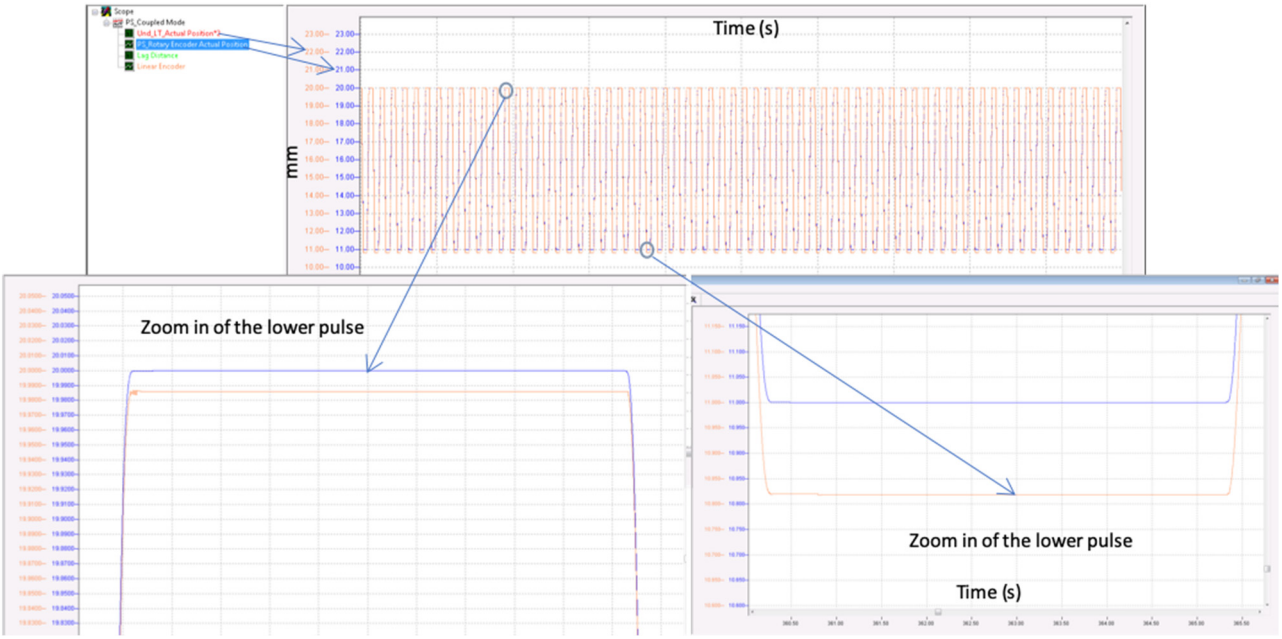

Figure 4: The repeatability of the phase shifter gap positioning by following the undulator from gap 20 mm to 11 mm and backwards. The dependency is set 1:1. The red curve shows the position of the undulator gap, the blue one, the position of the phase shifter gap.

TEST OPERATION AT THE SASE3 UNDULATOR SYSTEM

The behaviour of the modified phase shifter in the accelerator environment during use in operation has been done. The main idea was the investigation and comparison of the influence of radiation showers on both, direct measurement system based on an incremental linear encoder and the indirect system based on the absolute rotary encoder gap readout systems. To accomplish it, the complete modified phase shifter has been installed in the first cell of the SASE3 undulator system. This cell has been selected because a) presently cells 1 and 2 are vacant and no undulator and phase shifters are installed and b) relative large radiation doses have been detected at the beginning of SASE 3 undulator system. Based on observations with unupgraded phase shifters, which were using linear encoders, occasionally sudden gap changes without any movement were happening. It was supposed that radiation showers may affect, i.e. change the reading of the incremental encoders leading to a change of the displayed gap but without any movement. For verification, the difference between the linear and rotary encoder values has been monitored as a function of time using a dedicated monitoring software. The readings of the absolute rotary encoders are belived to be inert to radiation showers, since their values are absolutely decoded. In addition the encoder is about 0.5m above the beam axis leading to a lower exposure than the incremental encoders, which are closer to the beam. A log file was recorded over 125 days from 04.07.2018 to 09.10.2018. The readout data frequency has been selected once every 10 minutes.

The Fig. 5 shows the difference between the linear and absolute encoder values over the whole monitoring time of 125 days.

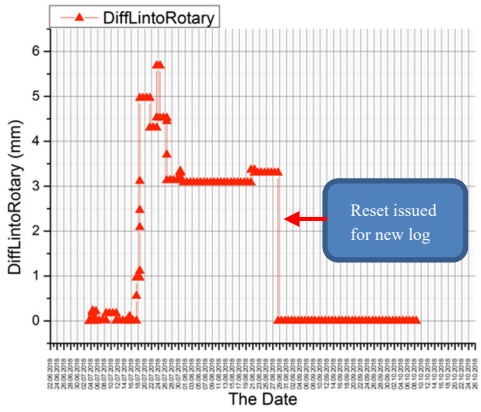

Figure 5: The jumps of linear encoder values without issuing the movement command of the phase shifter gap. Small changes (less than 1mm) are neglected, considered as noise.

As can be seen in the plot, non zero differences are observed. A sudden jump is called an event. It is a sudden jump in the difference without any gap movement, since the rotary encoder values remain unchanged. It is seen that there are many jumps of different magnitude, ranging from ≈0.1 mm to about 5.5 mm. Taking into the account beam interruptions during the monitoring period there is a considerable number of jumps just for one cell. A forecast to an undulator system consisting of 35 cells suggests a high error rate for the gap readings of phase shifters.

CONCLUSION

The planned modification of the phase shifter using servomotors and absolute encoder feedback was described, tested and done for all tree SASE undulator systems. The following main results have been achieved during tests performed in the lab:

- A software solution namely Image Distribution and Automation (IDA) for controlling various configuration aspects of the undulator control system has been developed in-house [3]. IDA software was heavily used during the configuration of the 88 phase shifter in the tunnel. Correction coefficients measured previously are stored in the central database for each phase shifter. During the system upgrade, IDA was configuring each cell's PLC software with its own parameters such as correction coefficients and position bias.
- A maximum difference of 16 µm deviation between the rotary and linear encoders values has been measured after applying the correction coefficients.
- The maximum observed hysteresis of 4 µm has been detected.
- Servomotors significantly improve operational functionality and increase the motion dynamic range.
- In the coupled mode the phase shifter axis shows the good repeatability of the gap positioning and follows the undulator axis.
- The lag distance is depending on the undulator axis speed, and it's practically negligible if the undulator axis speed override value is set to 0.1%.

Based on the results of the measurements described above, the following conclusions were made:

- Operation in the accelerator environment clearly showed that radiation showers lead to a change of the displayed gap but without any real movement.
- Therefore the absolute rotary encoders significantly increases the reliability of gap readout.
- Including spares, the upgrade of 107 phase shifters with the ICRs has been done without interruption of the operational schedule.
- The installed incremental encoders were not removed. They were used for initializing the absolute encoder to obtain a gap reference value.
- After the modification campaign, the significant increases of the phase shifters operational reliability was observed during the last nine-month of the facility operation. Besides the reliability, the time-saving aspect is another valuable improvement which is crucial while changing the undulator system parameters.

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