PRELIMINARY DESIGN OF MOTOR DRIVERS FOR THE SHENZHEN SUPERCONDUCTING SOFT X-RAY FREE ELECTRON*

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Abstract

This paper presents the preliminary design of two motor drivers developed for the S³FEL(Shenzhen Superconducting Soft X-ray FEL) project: one for cavity tuning and the other for coupler adjustment. Both drivers control stepper motors to regulate the resonant frequency and coupling degree of the 1.3GHz superconducting cavities, respectively. Each driver comprises two functional modules: a motor driver board and a limit signal conditioning circuit. The driver board translates low-power control signals (enable, direction, speed) into high-power outputs to drive the motor. Key design features include optocoupler-based isolation between control and power stages to prevent interference, subdivided stepping for improved positioning accuracy and motion smoothness, and real-time current monitoring to ensure correct output. The limit signal conditioning circuit provides excitation to the limit switches, samples their status, and returns the signals to the controller. Both drivers also supply a holding current to maintain motor position when stationary. Experimental validation confirms that the designed drivers satisfy the operational requirements for precise tuning and coupling control in the S³FEL system.

INTRODUCTION

Stepper motors are widely used in various precision positioning systems owing to their simple open-loop control and high positioning accuracy [1]. In an accelerator, the tuner is driven by a stepper motor mounted external to the cryomodule that transfers torque through two rotary feedthroughs and the coupler is also driven by a stepper motor to control the coupling strength between the superconducting cavity and the external RF line by varying the depth of the coupling probe. However, in applications requiring high reliability, such as superconducting cavity tuning in particle accelerators, present several challenges for traditional stepper motor drivers:

1. Electromagnetic interference (EMI) generated by high-voltage, high-power drive circuits [2].
2. Low-frequency oscillation [3] and step loss [4] are prone to occur at low speeds.
3. The inability to retain motor position memory and automatically return to a safe position poses a significant risk of damaging expensive superconducting cavities.

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SYSTEM ARCHITECTURE

A standard 1.3GHz cryomodule at S³FEL contains eight superconducting RF cavities with eight coupler motors and sixteen tuner motors [5, 6]. Coupler motors are used to adjust the coupling coefficient of the superconducting cavity and tuner motors are used to tune the resonant frequency of the superconducting cavities. S³FEL includes 222 coupler motors and 219 tuner motors. Each motor needs a motor driver, the driver for two types of motors are quite different because of the different rated operating parameters. Two types of motor are shown in Fig. 1 and Fig. 2.

Figure 1: Coupler motor.

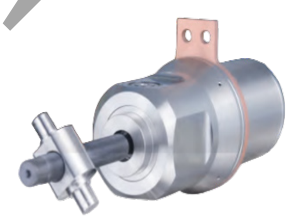

Figure 2: Tuner motor.

The operating parameters of the motors are shown in Table 1.

Table 1: Motor Parameters

Parameter	Coupler Motor	Tuner Motor
Rated Voltage	5V	24V
Rated Current	1.3A	1.2A
Phase	2	2
Step Angle	1.8°	1.8°
Step	0.003175mm	0.0001mm

MOTOR DRIVER DESIGN

Optocoupler-isolated Signal Transmission

To prevent electromagnetic interference (EMI) and ground potential drift from the rear-stage high-power circuit (strong-current side) to the front-stage controller (low-voltage side), the driver incorporates high-speed optocoupler circuits at the signal receiver end. The transmission design is shown in Fig. 3.

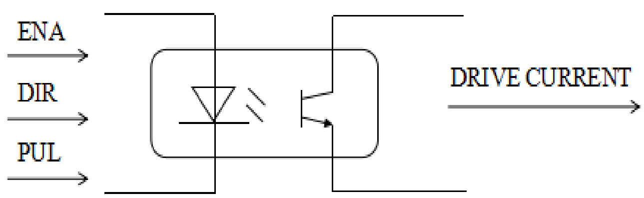

Figure 3: High-speed optocoupler circuit.

Specifically, the pulse (PUL), direction (DIR), and enable (ENA) signals from the controller are first electrically isolated by high-speed optocouplers. Current-limiting resistors are connected in series at the input side of the optocouplers. This design achieves complete isolation between the input signals and the control power supply. Consequently, this not only protects the controller from high-voltage surges but also effectively suppresses ground loop noise, ensuring the integrity of weak control signals and preventing interference from motor power signals.

Microstep Control and Low-Frequency Oscillation Suppression

The inherent step angle of stepper motors results in noticeable "stepping" and low-frequency vibration at low speed, thereby limiting the system's positioning accuracy. To address this issue, the driver adopts microstep drive technology to sinusoidalize the output current. Microstep configuration ensures a smooth transition of the stepper motor winding current, mitigating abrupt torque fluctuation and effectively suppressing motor resonance. This reduced resonance significantly minimizes jitter in the coupler probe and tuner

Since both the coupler and tuner motors are 2-phase, the driver is designed to output 2-phase currents accordingly. Microstep control method is shown in Fig. 4 and Fig. 5.

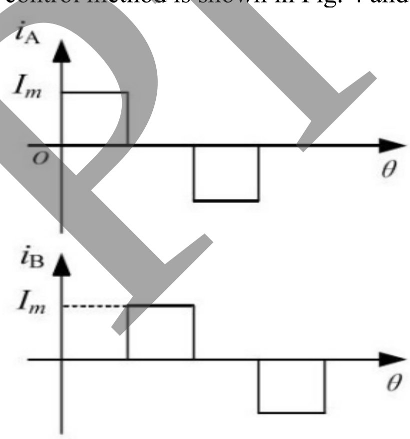

Figure 4: Drive current before microstep.

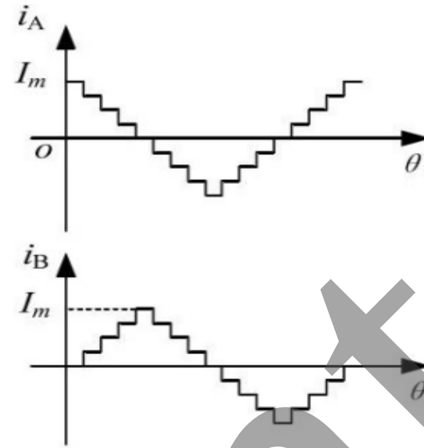

Figure 5: Drive current after microstep.

The driver subdivides a full step into multiple microsteps. Its operating principle involves applying a staircase-modulated sinusoidal current to the windings, thereby smoothing the rotation angle of the stator magnetic field. With this subdivision strategy, the step angle of the coupler motor is reduced from 1.8° to 0.007°, and that of the tuner motor from 1.8° to 0.014° , significantly enhancing the positioning accuracy.

Limit and Position Monitoring

The driver provides dedicated interfaces for positive and negative limits, compatible with normally closed (NC) mechanical micro-switches. When the motor reaches a limit position, the switch opens, sending a signal to the controller. Upon detecting a valid limit signal, the controller immediately disables pulse output and prohibits further movement in that direction, thereby achieving a hardware emergency stop to prevent mechanical overrun and potential damage.

Furthermore, to enable real-time motor position monitoring, the driver incorporates an automatic counting function. The system captures pulse signals via internal timers and updates a position counter in real time—incrementing or decrementing based on the movement direction. This counter is backed up in non-volatile memory (EEPROM), which records the motor's direction and cumulative step count. Consequently, the system maintains accurate knowledge of the current relative or absolute position, regardless of whether the motor is running or stationary.

TEST PLATFORM

This paper developed a motor control system including a MTCA crate, control boards and a motor driver. The control board and motor driver are all developed by our team. The above devices will be used in the S3FEL to control the coupling and frequency of the superconducting cavities. The motor control system can adjust the operating status of S3FEL through users' requirement and make sure the safety of the S3FEL. The system is shown in Fig. 6, Fig. 7 and Fig. 8.

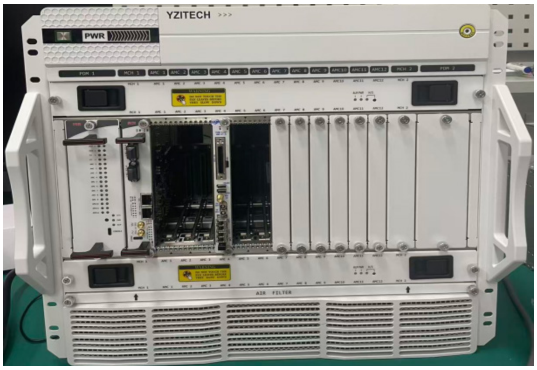

Figure 6: MTCA crate.

Figure 7: Motor control board.

Figure 8: Motor driver.

This paper used the self-designed MTCA crate, motor control board and motor driver to create a laboratory test platform shown in Fig. 9.

Figure 9: Test platform.

PRELIMINARY TEST RESULTS

Through the platform, preliminary tests were conducted to verify the functionality of the motor driver. Motor start/stop, forward/reverse rotation, and limit functions operate normally. Communication between the driver and the controller functioning properly. We have resolved the interference from the power signal to the limit signal in the engineering implementation.

CONCLUSION

A motor driver and control system of coupler motor and tuner motor in superconducting cavities for S3FEL has been created and initially tested. By employing high-speed optocoupler circuits, microstep drive technology, and limit/position monitoring functions, the driver effectively mitigates the impact of rear-stage high-power signals on front-stage control signals. This approach reduces low-frequency vibration during motor operation while significantly improving positioning accuracy. Furthermore, it enables real-time position monitoring and allows the motor to automatically return to the origin along a deceleration curve in case of a cavity warm-up event. An experimental platform was also established to preliminarily verify the basic functions of the driver, successfully resolving the issue of crosstalk between power and control signals.

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