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This paper presents the design of the actuator for the fast and high accuracy Wire Scanner system. The actuator consists of a rotary brushless synchronous motor with the permanent magnet rotor installed inside the vacuum chamber and the stator installed outside. The fork, permanent magnet rotor and two angular position sensors are mounted on the same axis and located inside the beam vacuum chamber. The system has to resist a bake-out temperature of 200 C and ionizing radiation up to tenths of kGy/year. Maximum wire travelling speed of 20 m/s and a position measurement accuracy of 4 um is required. Therefore, the system must avoid generating vibration and electromagnetic interference. A digital feedback controller will allow maximum flexibility for the loop parameters and feeds the 3-phase linear power driver. The performance of the presented design is investigated through simulations and experimental tests.

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Abstract

This paper presents the design of the actuator for the fast and high accuracy Wire Scanner system. The actuator consists of a rotary brush-less synchronous motor with the permanent magnet rotor installed inside the vacuum chamber and the stator installed outside. The fork, permanent magnet rotor and two angular position sensors are mounted on the same axis and located inside the beam vacuum chamber. The system has to resist a bake-out temperature of $200^{\circ}\mathrm{C}$ and ionizing radiation up to tenths of kGy/year. Maximum wire travelling speed of $20\ \mathrm{m.s^{-1}}$ and a position measurement accuracy of $4\ \mu m$ is required. Therefore, the system must avoid generating vibration and electromagnetic interference. A digital feedback controller will allow maximum flexibility for the loop parameters and feeds the 3-phase linear power driver. The performance of the presented design is investigated through simulations and experimental tests.

INTRODUCTION

The accurate measurement of the transverse beam intensity is one of the key factors for the optimisation of the luminosity in the Large Hardron Collider (LHC). This measurement can be performed by different kinds of instruments using interceptive and non interceptive methods. The Wire Scanner (WS) is an interceptive method and is often used to calibrate the other instruments. It measures the transversal beam density profile by means of a thin wire passing through the beam intermittently. When the wire passes through the beam particles, the interaction generates a cascade of secondary particles, which are intercepted by a scintillator coupled with a photomultiplier. Thus, the generated current at the output is proportional to the beam intensity at the position of the wire. The wire position and the intensity signal data are combined to reconstruct the transversal beam density profile.

To reach the target performance, including a wire travelling speed of up to $20\ \mathrm{m.s^{-1}}$ and a position measurement accuracy of the order of $4\ \mu\mathrm{m}$ with an minimum acquisition frequency of $286\ \mathrm{kHz}$ [1], a new approach taking into account radiation, bake-out temperature and the ultra high vacuum (UHV) environment is proposed.

The new wire scanner concept places all moveable parts in the vacuum chamber. The proposed solution to drive the forks, uses a permanent magnet rotor placed in a vacuum chamber coupled to a stator through a wall of zero magnetic permeability stainless steel (Fig. 1). This method avoids the use of bellows.

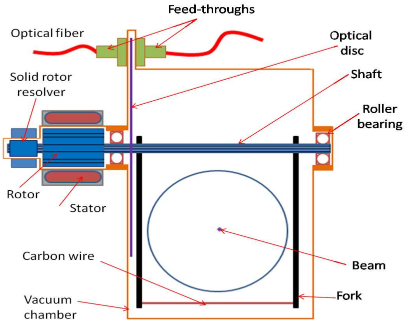

Figure 1: Simplified drawing of the future wire scanner. The orange lines show the vacuum barrier.

The rotor is fitted on a shaft supported by roller bearings. Materials and solid lubricants for the roller bearings have to be selected for low outgassing and friction requirement coming from the vacuum environment. The wire is stretched between fork arms which are attached to the shaft. Two position transducer, mounted on the rotating shaft, will provide the absolute angular position for the feedback control loop of the motor and high accuracy determine the wire position.

REQUIREMENTS

A scan represents an angular movement of $\pi\ \mathrm{rad}$ (half turn) including a phase of acceleration, deceleration and constant speed. The required wire travelling speed is $\mathrm{V_{max}} = 20\ \mathrm{m.s^{-1}}$ corresponding to $\omega_{\mathrm{max}} = 210\ \mathrm{rad.s^{-1}}$ for a fork length $\mathrm{L_{fork}} = 100\ \mathrm{mm}$. The actuator must provide enough torque to allow the optimisation of the profile of acceleration, speed and position. The maximum angular speed has to be reached in less than 1/6 of turn i.e. a minimum angular acceleration of $\alpha_{\mathrm{req}} = 20\ 000\ \mathrm{rad.s^{-1}}$ (assuming a constant acceleration profile).

The motor air gap must be large enough to allow a zero magnetic permeability stainless steel wall of $0.3\ \mathrm{mm}$ to be inserted [2]. Moment of inertia of turning parts (rotor, fork, shaft, angular sensor) has to be minimised to reduce the required accelerating torque.

The angular position measurement must provide information for two different purposes: First, the absolute angular position readout allowing a accurate motor control with an accuracy better than 20 arc minutes r.m.s. [3] and secondly the measurement of the wire position with an accuracy of $4\ \mu m$ i.e. angular position measurement of about 5 arc seconds r.m.s. considering a fork length of $100\ \mathrm{mm}$. An acquisition is needed every $70\ \mu\mathrm{m}$ i.e. a frequency of

286 kHz (at 20m/s) . The processing of the signal will be performed offline.

ACTUATOR DESIGN

The maximum required torque $\mathrm{T_{max}}$ is the sum of the accelerating torque $\mathrm{T_{acc}}$ and the additional torque T_{add} which compensates frictions and resistive torque due to Eddy currents in the vacuum barrier.

Accelerating torque $\mathrm{T_{acc}}$ is given by Newton's law:

$$T_{acc} = J_{total} \cdot \alpha_{req} = 11.6\ Nm$$

where $\mathrm{J_{total}}$ is the total moment of inertia of shaft, fork, angular sensor and rotor, α_{req} is the required angular acceleration.

Additional torque $\mathrm{T_{add}}$, depends on the geometry, the resistivity of the vacuum barrier, the flux in the air gap, the friction and the angular speed of the rotor (ω_{r}). It is measured:

$$T_{add}(\omega_r) \approx (0.2 + 0.013\omega_r)\ Nm$$

So, the maximum required torque, when ω_r is maximum $(\omega_r = \omega_{r_{max}})$ is given by:

$$T_{max} \approx T_{acc} + T_{add}(\omega_{r_{max}}) \approx 14.6\ Nm$$

The Parker K500150 frameless PMSM has been selected. Its peak torque $T_p = 23.76\ Nm$ is greater than the maximum required torque $\mathrm{T_{max} = 14.6\ Nm}$. Furthermore, its nominal torque $\mathrm{T_N = 7.92Nm}$ is greater than the equivalent rms torque $\mathrm{T_{rms} = 2.98\ Nm}$ [4].

Samarium cobalt alloy has been chosen as adequate magnetic material for the rotor, instead of standard neodymium which is less resistive to temperature. These kinds of motors are supplied in two independent parts: three-phase stator and a rotor with permanent magnets mounted on the surface.

A solution has been proposed based on 3-phase linear power supply, containing 3 power operational amplifiers used in no-inverting configuration.

The peak required current $\mathrm{I_{peak}}$ for the motor is given by:

$$I_{peak} = T_{max}/k_T = 32.44\ A$$

where $\mathrm{k_T}$ is the torque constant.

Considering the specifications listed above, the Apex PA52 power operational amplifier has been chosen. It can provide an output voltage of 200 V, a peak current of 80 Amps and a gain-bandwidth product of 3 MHz.

Two independent angular position sensors have been proposed to meet the specifications: an absolute Rotasyn® solid rotor resolver for the feedback of the motor and an incremental ad hoc optical fiber based encoder for the high accuracy determination of the wire position.

Rotasyn® solid rotor resolver, which unlike the traditional brushless resolver, has both primary and secondary windings in stator, thus no rotary transformer is required [5]. In this configuration the resolver provides an accuracy of +/- 60 arc minutes.

The calibrated resolver position measurement does not reach the specified accuracy for the determination of the wire position. The proposed solution consists of an ad hoc optical fiber based rotary encoder. It consists of a rotating disk, two optical fibers feedthroughs and a deported optoelectronics interface. The disk, mounted on the shaft, has patterns of opaque and transparent sectors printed on it by a photolithography process. As the disk rotates, these patterns interrupt intermittently the laser beam between the two optical fibers. The optoelectronics interface, located up to 250m far away, processes the modulated light to accurately determine the relative position of the wire. In order to validate this optical fiber encoder a test bench has been produced. Where the optical fibers can be set in different relative positions by means of 2 sets of 3 axis linear stages (Fig. 2).

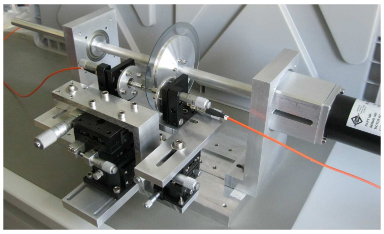

Figure 2: Picture of the optical fiber encoder test setup.

STUDY VALIDATION BY SIMULATION

The WS actuator is simulated in Simulink® to demonstrate the performance of the proposed design. The general structure of the simulation setup is illustrated in Fig. 3. It consists of a PMSM and 3-phase linear power supply model, integrated in a vector control closed loop allowing a control of the angular speed of the rotor (ω_{r}). The following parameters motors were extracted from the motor datasheet and have been validated by parameters measured on the test bench:

$R_s = 0.245\ \Omega$, $L_s = 1.365\ mH$, $k_E = 0.2598\ V.rad^{-1}.s^{-1}$, $k_T = 0.45\ N.m.A^{-1}$, $p = 4$, $J_{total} = 5.8.10^{-4}\ kg.m^2$, respectively, stator resistance and inductance, voltage constant, torque constant, pole pairs, total inertia.

As seen in the Fig. 4, the speed reaches peak angular speed at $\pi/3$ rad. Fig. 5 shows the 3-phase currents which meet the capability of the amplifiers.

EXPERIMENTAL TESTS

A test bench has been designed and built as shown in Fig. 6. Its mechanical part consists of a shaft, a frameless PMSM including a no magnetic shielding cylinder, a DC motor, a high accuracy optical encoder and a solid rotor resolver. The electrical part of this bench contains a three

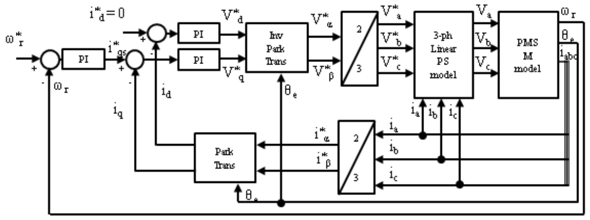

Figure 3: Simulation model.

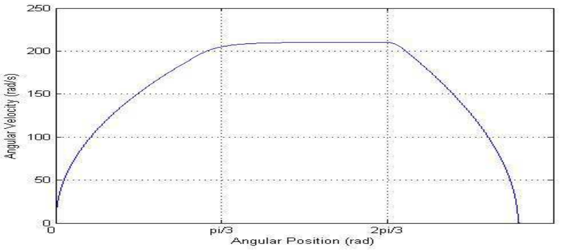

Figure 4: Angular speed vs angular position of the motor.

phase linear amplifier, a capacitors pack and a DSPACE real time control interface. The developed bench allows characterisation of the PMSM and resolver, testing the actuator functionalities and developing the control strategy of the motor. At the current stage of the project, all the components are mounted on the bench. Measurements of the motor and power supply parameters have been done.

Fig. 7 shows that the measured ElectroMotive Force (EMF) voltage of the 3 phases have the expected shape (sinusoidal).

The resolver has been calibrated according to the high accuracy optical encoder. The error compensation information has been stored in a look − up table which corrects acquisition one-by-one. This procedure has improved the angular accuracy from +/- 60 arc minutes to +/-6 arc minutes which satisfy the specifications for the motor control (Fig. 8).

CONCLUSION

In this paper, the design of the actuator for the fast and high accuracy wire scanner has been presented. The proposed design has been validated by a simulation study. A test bench has been built, tested and is now ready for the development of the control algorithm strategy regarding the vibration phenomenon and disparities of the physical parameters of the motor, power supply and long cables.

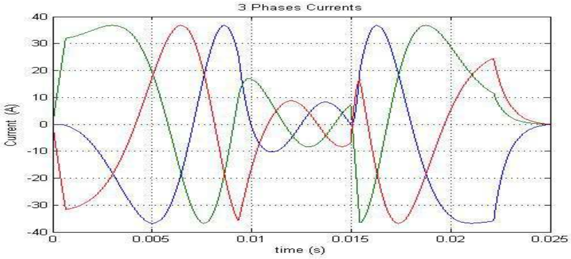

Figure 5: 3-phase currents of the motor vs time.

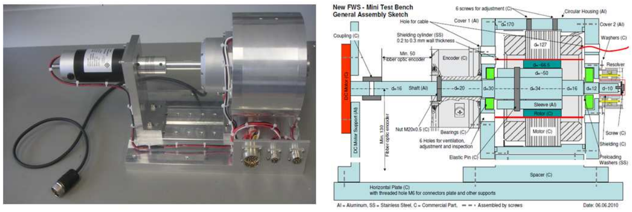

Figure 6: Picture of the test bench.

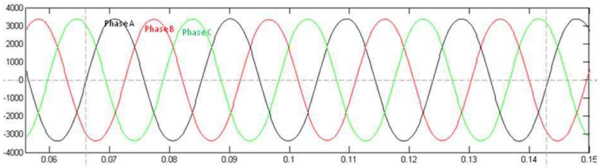

Figure 7: Measured Electromotive force (EMF) voltage of 3 phases.

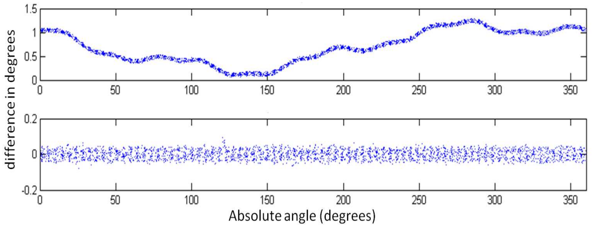

Figure 8: Difference between the resolver and the encoder measurement according to the encoder angle. Top) Before the calibration. Bottom) After the calibration.

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