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New sensor and non-contact geometrical survey for the vibrating wire technique

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ABSTRACT

The tolerances for the alignment of the magnets in the girders of the next machine of the Brazilian Synchrotron Light Laboratory (LNLS), Sirius, are as small as 40 μm for translations and 0.2 mrad for rotations. Therefore, a novel approach to the well-known vibrating wire technique has been developed and tested for the precise fiducialization of magnets. The alignment bench consists of four commercial linear stages, a stretched wire, a commercial lock-in amplifier working with phase-locked loop (PLL), a coordinate measuring machine (CMM) and a vibration sensor for the wire. This novel sensor has been designed for a larger linear region of operation. For the mechanical metrology step of the fiducialization of quadrupoles an innovative technique, using the vision system of the CMM, is presented. While the work with *pitch* and *yaw* orientations is still ongoing with promising partial results, the system already presents an uncertainty level below 10 μm for translational alignment.

1. Introduction

In December 2014, the construction of Sirius, the new particle accelerator at the Brazilian Synchrotron Light Laboratory (LNLS) has officially begun, on the campus of the Brazilian Center for Research in Energy and Materials (CNPEM). It promises to be the brightest light source of its kind, comparable only to MAX IV, in Sweden. It is also considered the greatest scientific project in Brazil, raising competitiveness in fields of research such as materials science, medicine, biology and chemistry. For the accelerator to perform as designed, however, the demands on engineering are extremely high. High precision in the alignment of the magnets is particularly important. The x and y RMS alignment requirements of quadrupoles and sextupoles in a girder has been specified to within 40 μm, while the rotational tolerances for *pitch*, *yaw*, and *roll* are of only 0.2 mrad [1].

The geometrical and magnetic axes of multipole magnets may differ by a few micrometers [2], due to fabrication processes, mounting repeatability and variations in material properties. Therefore, to perform an alignment using the physical body of the magnet, it is necessary to find its magnetic axis and correlate it to external fiducials. This process is known as the fiducialization of a magnet, which is in this paper (as in [2]) divided in two steps, namely: finding its magnetic axis using a magnetic survey technique and relating the magnetic center axis to a frame in the magnet yoke using a geometrical survey technique. This second step is often divided in two steps, due to an indirect measurement of the magnetic axis position [3]. In any case, several techniques have been employed for both kinds of surveys [4,5].

As for the magnetic survey, the vibrating wire has been proposed in [6] as an evolution of other wire techniques, as the moving, the pulsed and the stretched wire techniques, with the particular advantage of precisely (and univocally) determining the magnetic axis of magnets [4,5]. Since then, it has been successfully implemented in the alignment and fiducialization of multipole magnets and solenoids [3,4], [6,7,8,9,10,11,12], as well as the characterization of insertion devices, such as superconducting wigglers and undulators [13,14,15]. Another technique that is often used for magnetic survey is the rotating coil. It is very powerful for multipole characterization of magnets [16] and can also be used to find the magnetic axis of a given magnet [2], although it is rather limited in the precise determination of the coil axis to a few tens of micrometers [4]. Nonetheless, this technique may conveniently support the vibrating wire in the fiducialization of the *roll* angle, to which the latter is essentially insensitive.

Today the most used geometrical survey methods are portable coordinate measuring systems, like measuring arms and laser trackers, or fixed coordinate measuring machines [2,3,4,17]. Other techniques, like the use of traditional theodolites or laser

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interferometry have either larger uncertainty or more complicated setup specifications for their use, and usually require triangulation methods and the use of multiple instruments [5]. Portable coordinate measuring systems have the advantages of providing relatively small uncertainties with a large measuring volume and flexibility. However, in order to achieve rigorous alignment tolerances redundant measurements from different instrument locations need to be performed [18]. All considered, it is believed that the lowest uncertainty can be achieved with a coordinate measuring machine (CMM) [3]. Finally, as far as the vibrating wire is concerned, to the best of our knowledge, the geometrical survey is always performed by indirectly finding the position of the wire via a non-contact sensor with fiducial references, which are later related to the fiducial references in the magnet. In this work, a new approach is proposed to directly measure the wire and the references in the magnet by means of non-contact probing.

In the following the development of the vibrating wire measurement bench at LNLS, which will be used for the fiducialization of Sirius magnets, is presented along with the first results. It consists of a tungsten wire of 0.1 mm of diameter, which is stretched through one or more magnets and moved by linear stages, at the same time that an alternating current runs through it. If the local magnetic field is different from zero and the frequency of this electric current matches one of the harmonics of the wire, a resonant vibration with high sensitivity is observed. The tungsten wire was chosen due to higher ultimate tensile strength, if compared to other material choices, such as CuBe alloy. Also, tests with the optical system were performed and a higher contrast was achieved with the tungsten wire. The schematic of the bench is shown in Fig. 1. A new vibration detector to perform the magnetic survey has been developed to provide a wider range of operation than it is typically found in the literature. This paper describes its design, test and use for the measurement of a quadrupole magnet, and details the new strategy used in the geometrical survey measurements.

The current alignment strategy for Sirius magnets within a girder relies on self-alignment achieved by design tolerances. The magnets are being developed and manufactured in such a way that the magnetic axis should be coincidental with the geometrical axis, to a certain level. After mounting, the magnets will be aligned by definition. This micro-alignment approach depends on the previous statement about the location of the magnetic axis of each magnet, which needs to be verified. A macro-alignment step will be the tridimensional positioning between girders, and for this task a combination of survey engineering with large-scale metrology shall be used. The vibrating wire technique is being developed to the main goal of checking the magnetic axis location and orientation of a certain magnet, like quadrupoles and sextupoles. The technique is then needed to validate the aforementioned micro-alignment by construction. The idea is to to use the technique to inspect the magnets, in the case of random sampling or performing complete inspection (100% of the manufactured magnets), type of inspection to be decided.

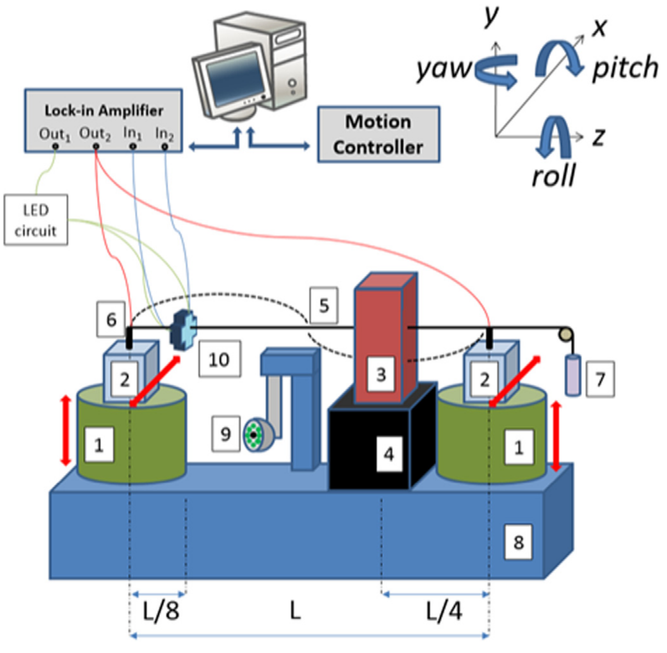

Fig. 1. Schematic of the vibrating wire bench at LNLS: (1) vertical linear stages; (2) horizontal linear stages; (3) magnet; (4) magnet support; (5) wire; (6) wire end; (7) hanging mass; (8) CMM; (9) CMM optical probe; (10) horizontal and vertical vibration detectors.

2. Setup description and procedures

The physical and mathematical description of the experiment has already been fully developed and discussed elsewhere [4,6], therefore, it will not be repeated here. However, it is important to emphasize that placing the magnets and the vibration detectors at convenient positions along the wire makes the technique particularly sensitive to translational or rotational misalignments. For a given length of the wire, L, the magnet is positioned at $z = L/4$ and the detectors at $z = 7L/8$. In this configuration the second harmonic of the wire has a peak at the magnet position, so that the excitation for translational misalignments is maximized and there is a good sensitivity for the detector. Likewise, the fourth harmonic has a node at the magnet position and a peak at the detector position, maximizing the excitation for rotational misalignments and the sensitivity for the detector. This was the configuration that was adopted with a 1.2 m long wire. In this case the fundamental mode of the wire is at a frequency equal to 140.5 Hz.

For the detection of the vibration of the wire, a novel sensor has been developed with a Hamamatsu S5870 multi-element photodiode, providing an operational range that is ten times larger than the typical H21A1 phototransistors which are used in different vibrating wire setups [6,7,8]. Moreover, after the work at the Paul Scherrer Institute (PSI) [10,11], all the electronics is managed by a Zurich Instruments HF2LI dual-channel lock-in amplifier, using the phase-locked loop (PLL). This resource is especially useful since the ends of the wire are moved with respect to the magnet, resulting in eventual variations in the resonant frequency, due to changes in the wire length and friction.

Since the beginning of the project, it was clear that most measuring items, such as theodolites or articulated measuring arms, would hardly meet the tolerances for the mechanical metrology step [3,5,7]. For this reason, the bench has been built on a *Global Performance Silver Edition* 12.30.10-*Brown & Sharpe Hexagon Metrology* CMM, as seen in Fig. 2, which opened the possibility for the innovative metrology technique for this application, based on its vision system.

2.1. Linear stages and mechanical alignment

In order to avoid mechanics to move the different magnets that will be fiducialized, the choice was to move wire ends instead. This option would also allow for multiple magnets to be aligned in a girder, for instance [8]. For that, two pairs of XY linear stages have been purchased from Huber: models 5101.20-XE for x motion and 5103.A20-40-XE for y. Despite the integrated encoders, the quality of motion was checked with an Automated Precision Inc. (API) XD6 laser interferometer, as shown in Fig. 3.