EXPERIMENTAL VALIDATION OF SOLENOID MAGNETIC CENTRE MEASUREMENT BY VIBRATING WIRE SYSTEM

P. Arpaia[1], C. Petrone[1,2], and L. Walckiers[2]

[1]University of Sannio, Benevento, Italy, carlo.petrone@cern.ch
[2] European Organization for Nuclear Research, Geneva, Switzerland.

Abstract: A method to measure the magnetic axis position of a solenoid magnet by means of a vibrating wire is proposed. The method allows the magnetic axis to be found in spite of the low transversal field. The experimental results of the magnetic axis measurements on a prototype solenoid magnet of the linear accelerator for the low energy beam transport line at CERN are illustrated.

Keywords: Electromagnetic Fields, Vibration Measurement, Measurement Science, Force Measurement.

1. INTRODUCTION

Finding the magnetic axis of quadrupole and higher-order magnets is an important issue for good performance of particle accelerators [1]. This is a challenging measurement for small-aperture magnets currently developed for future accelerator projects. The sensitivity of the classical measurement method, the single stretched-wire (SSW) is poor due to small displacement amplitudes [2]. A moving wire, cutting the flux lines in the magnet, produces a proportional electrical voltage. The difference of integrated voltages measured between two opposite wire displacements gives the offset of the starting point with respect to the magnetic axis. Another method is vibrating wire [3]. A wire fed by electrical current is oscillated perpendicularly to the local transverse magnetic field component and proportionally to both current and field magnitudes. A sinusoidal current reaches the maximum amplitude at the wire resonance frequency. Sensitivity in the micrometre range is easily achieved [4].

A solenoid is a magnet designed to produce a uniform magnetic field in a volume of space, where the field line are mainly parallel to the magnetic longitudinal axes. Information on the field quality is gathered by measuring the field in the magnetic aperture as a whole through a Hall probe [5]. This measurement is usually carried out using a three-axis coordinate stage controlled by a computer, but it is a quite tedious procedure.

In the following, a very sensitive method to locate the magnetic axis position in a solenoid magnet using a vibrating wire is proposed. In particular, in Section 2, the proposed method is described; in Section 3, the system set maximising the transversal field effect on the wire is discussed, and in Section 4, the experimental validation of the method is presented.

2. PROPOSAL

The vibrating wire system consists of a thin wire passing through the magnet and stretched by means of a weight or a motor. Two high-precision stages move the wire to be aligned with the solenoid axis. A current generator feeds the wire with a sinusoidal current.

To locate the centre in a solenoid magnet, a wire oscillation is induced by a current at the fundamental frequency or a higher mode. In Fig. 1, the force on the wire (vertical arrows) using the second fundamental frequency of the wire is highlighted.
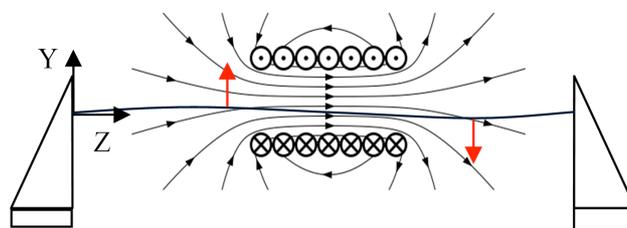

Fig. 1 Resulting forces on the wire (red vertical arrows) using the second wire fundamental frequency (Y: vertical axis, Z: axial direction.).

The fundamental wire frequency is estimated by kicking the wire and making a Fourier analysis of the voltage signal from optical sensors measuring the wire movement. The second harmonic is accurately tuned by searching the maximum amplitude for this signal. The optical sensors, suitably positioned on the wire, transduce the wire displacement to an electrical voltage. By means of signal amplifiers, an antialiasing filter and an analog-to-digital converter, a computer acquires voltage signals from both optical sensors and across a shunt for the sinusoidal current. The amplitude of the current to be fed into the wire has to be set properly in order to see the amplitudes of mechanical vibrations in the linear range of the optical sensors.

3. MEASUREMENT SET UP

A Cu-Be wire of 0.125 mm diameter is guided on both stages by ceramic ball-bearing and kept electrically floating. The wire length is 1830 mm and the mechanical tension 9.5 N is controlled by a tensioning motor, at one end, and a tension gauge at the other. The second resonance frequency was measured to be 139.702 Hz by finding the maximum amplitude response in frequency. The amplitude current on the wire is 105 mA, which is the maximum of the current generator of type Keithley 6221. The measurement was carried out by powering the magnet in DC current, i.e. at a value much lower than the operational field only obtainable in pulsed mode. Two perpendicular optical sensors (Sharp GP1S094HCZ0F) simultaneously measure the XY vibrations. The sensor outputs, after the pre-amplifiers and the anti-aliasing filters, are sent to the 18-bit acquisition system NI6289 of National Instrument. a shunt resistance measures the wire sinusoidal current. A motor controller Newport ESP7000 moves the stages. The position is accurately known from a linear encoder with ± 0.1 µm precision. The acquisition software is implemented by means of the Flexible Framework for Magnetic Measurements (FFMM) [6]-[7]. A Matlab^{TM} analysis program calculates the magnetic axis.

Reference fiducials are mounted on the stages. The precision of the respective wire position is known at ± 5 µm. An optical system refers the wire position to the external reference on the magnet, thus the magnetic axis is related to the two magnet fiducials by a LTD500 Leica Laser Tracker. The required absolute precision is ± 0.1 mm on the axis.

4. EXPERIMENTAL RESULTS

The magnetic axis was measured by two different methods, mapping and fitting, in order to have qualitative and quantitative information, respectively.

The first method maps the transverse field in the end regions of the magnet, by assigning the magnetic axis to the position where the oscillation is minimized. The scan is carried out with different steps and different angles for a better longitudinal resolution. In Fig. 2, a map of the wire amplitude oscillation (output voltage from the optical sensors) is shown as a function of the x and y positions after the alignment with respect to the magnetic axis. The map is based on steps of 0.2 mm in both directions.

The second method consists in acquiring the wire amplitude oscillation on a line trajectory. In particular, starting from a wire position around the mechanical magnet centre, iterative wire displacements of both parallel and non-parallel to the geometrical axis were imposed. Acquiring the wire amplitude in different points (Fig. 3) and by means of a linear fitting, the zero cross point gives the distance (Δ) between the zero wire position chosen as first reference (zero on the Cartesian axis) and the magnetic centre.
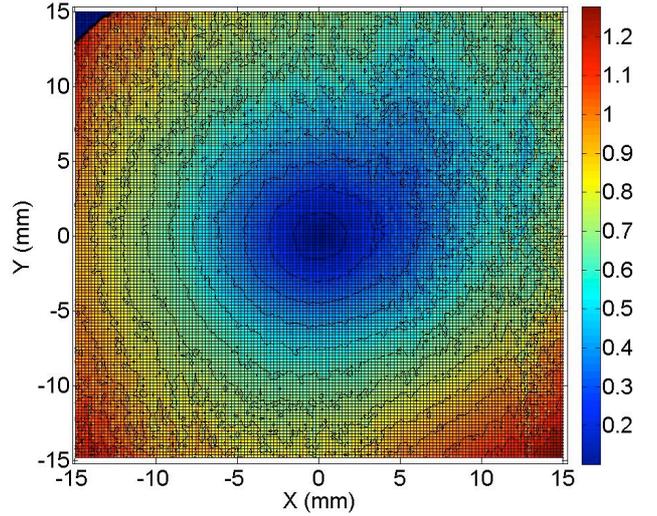

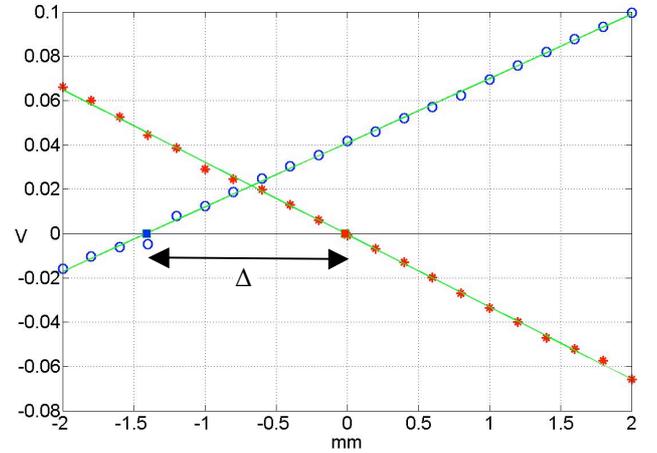Fig. 2: Field map by means of vibrating wire measurement

Fig. 3: wire amplitude oscillation with wire movements parallel to the magnetic axis both in X (o) and Y (*) direction. Δ gives the X difference between starting point and magnetic centre (in mm).

In Fig. 3, the horizontal wire amplitude oscillations (o in blue) are due to the vertical component of the field, while the vertical wire amplitude oscillations (* in red) are due to the horizontal field component.

By moving the zero reference of the stages in the new zero point, a new iteration can be done. The new measurement (Fig. 4) proves the magnetic centre and the wire positions to be coincident.

The same procedure can be done by moving the stages in opposite direction in order to maximize the parallelism between the wire and magnetic axis. In Fig. 5, the wire amplitude oscillation of the yaw angle (moving stages in X direction and pitch angle (moving stages in Y direction), are shown. The minimum amplitude (interpolated from the series of displaced measurements) is achieved at the magnetic axis of the solenoid. As highlighted in Fig. 5, the yaw angle corresponds to -0.04 mm displacement, and considering the wire length of 1850 mm, to 0.02 mrad ($\approx 0.04/1850 = 0.02$ mrad).
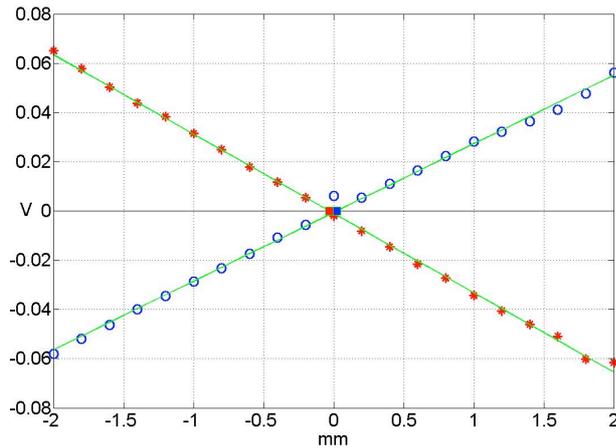
Fig. 4: wire amplitude oscillation moving the stages both in X (o) and Y (*) direction (in mm) after moving the starting point to the magnetic axis.
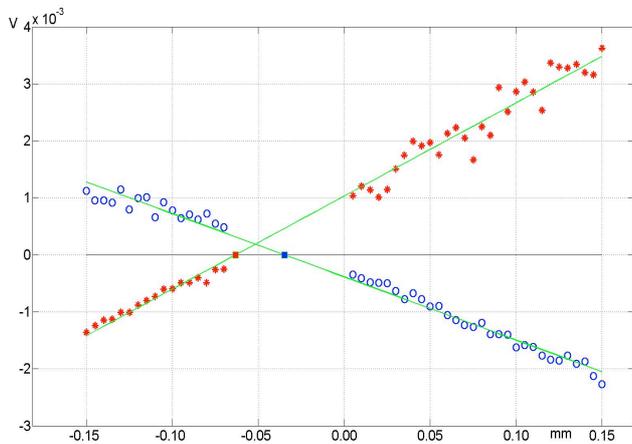

Fig. 5: Yaw (o blue) and Pitch (* red) wire amplitude displacement moving one stage in x and y direction respectively

The two ways to move the wire, parallel (Fig. 4) and non-parallel (Fig. 5) to the geometrical axis, must be iterate until the absolute minimum is found on both methods.

The magnetic centre referenced to the mechanical magnet position is measured by means of optical laser system. The reference system is shown in Fig. 6.

The wire sag (*s*) can be calculated as [8]:

$$s = \frac{g}{32 f_1^2}$$

where *g* is the standard gravity constant: 9.807 m/s^2 and *f* is the frequency of the wire fundamental resonance.
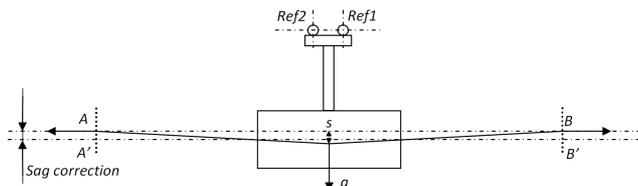

Fig. 6 shows the wire coordinate system with sag.

In this case, *f* is equal to 69.7 Hz; thus, the sag in the centre (*s*) is 0.063 mm. The uncertainty due to the real curve of the wire along the solenoid axis is neglected.

In Table 1, the values of the measurement achieved by the optical Leica system are shown. *AX, AY, BX,* and *BY* are the calibrated points on the stretched wire system to define the position of the wire when it is centred in the magnetic axis. A and B are the fixed points on the wire calculated from these last four points. The *Ref1* and *Ref2* are the fiducials on the magnet. The origin of coordinates is on *Ref1*. The upper plane of the magnet structure (yoke) is levelled to gravity, and not the line *Ref1* to *Ref2*. *Ref2* is used to define the horizontal axis (X). In Table 1, the values of the axis position with sag correction with respect to the references are shown.

	X (mm)	Y (mm)	Z (mm)	
A	-206.9	-628.0	994.7	
B	-197.0	-626.9	-851.7	
	X	Y	Z	sag
A'	-206.9	-628.1	994.7	0.063
B'	-197.0	-626.9	-851.7	
Ref1	0.0	0.0	0.0	
Ref2	0.0	0.0	-150.0	
angle(mrd)	-5.3	-0.6		

Table 1. the magnetic axis coordinates with respect to the fiducials, in mm and mrad.

According to these conventions, the results show that the misalignment between the magnetic axis and the geometrical axis is -5.3 mrad in the horizontal plane (yaw) and -0.6 mrad in the vertical plane (pitch). The angles are carried out by considering the wire length (1850 mm) and the differences of the point A' and B' in directions X and Y.

5. CONCLUSION

Solenoid magnets are mainly used in accelerators as beam focusing and the magnetic center must be aligned with the beam. The magnetic axis has been measured by the vibrating wire method. In fact, based on the vibrating wire effect, in spite of the low transversal field, the magnetic axis of a prototype solenoid magnet of the linear accelerator for the low energy beam transport line at CERN was found. Furthermore, the magnetic axis is also related to the mechanical references on the magnets mechanical structure.

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