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PERFORMANCE OF THE STRETCHED- AND VIBRATING-WIRE TECHNIQUES AND CORRECTION OF BACKGROUND FIELDS IN LOCATING QUADRUPOLE MAGNETIC AXES

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Abstract - A single conducting wire is used for localizing the magnetic axis of a quadrupole magnet. The localization is performed by both the stretched-wire and the vibrating-wire method. The compatibility of the two measurements is demonstrated and the measurement repeatability is assessed for both the methods at varying the magnet gradient. Furthermore, the influence of the background magnetic field in the two approaches is studied at varying the magnetic field strength. Experimental results are given for a normal-conducting quadrupole magnet.

Keywords: stretched wire, vibrating wire, magnetic axis, magnetic measurement

1. INTRODUCTION

Within the framework of the EU Project "Particle Accelerator Components Alignment and Metrology to the Nanometre scale" (PACMAN) [1][1], the magnetic axis of the main-beam quadrupoles for the CERN study Compact Linear Collider (CLIC) [2] has to be localized within an uncertainty in the micrometer range. The localization of the magnetic axis will give the reference for the correct positioning of the magnet inside the machine. The magnetic axis will be localized by means of a single conducting wire, stretched through the aperture of the magnet [3, 4].

The magnetic axis of a quadrupole magnet is defined as the locus of points within its aperture where the magnetic flux density is zero. As the wire transducer is sensitive to the integral field along its entire length, a distinction has to be made between the average magnetic center and the tilt of the axis. The first one results in a vanishing first field integral, while the second one results in a vanishing second field integral [5]. Both the criteria together determine the magnetic axis, often referred to as "true" axis. In a research cooperation between CERN, University of Sannio, and University of Napoli Federico II (Italy), the measurement of the average center is analyzed. Furthermore, as the main concern in this context is the performance of the wire as a magnetic transducer, the additional uncertainty caused by the transfer of the wire position from the local frame of the wire stages to the frame of the magnet is not taken into account.

Two different approaches are suitable for magnetic center finding. One consists in displacing the wire by moving its endpoints in the same direction (co-directional movement) and measuring the voltage induced in the wire loop caused by the magnetic flux variation [3, 6]. The measured voltage is then related to the offset between the initial position of the wire and the average center position. This method is referred to as the stretched-wire method and works well for large apertures (more than 10 mm radius) and high gradient fields (greater than 1 T integral gradient).

The second method makes use of a vibrating wire, tuned at the resonance frequency, which consists in measuring the vibration amplitudes and phases at different positions inside the magnet aperture, reached by displacing the wire ends co-directionally. The average center is then defined as the position where the vibration amplitude is zero [4, 7]. Due to the resonance condition, this method is characterized by a high sensitivity and is thus suitable for small apertures and low gradient fields.

The measurement performance of a method depends in general on the particular application. For instance, for the stretched-wire, the uncertainty achieved is within ± 5 μm for the axis of the quadrupoles for the LHC interaction regions. These magnets have a field strength of 215 T/m and a length of 6 m [3, 8]. The vibrating-wire method allowed the measurement of magnetic axis within uncertainty less than ± 5 μm for 0.15-m long quadrupoles, with 0.14 T peak field. A more recent setup, exploiting a phase-lock loop to follow the variations of the wire resonance frequency, allowed the axis of a quadrupoles to be found within a reproducibility in the sub-micron range [9].

Furthermore, a major issue when measuring magnetic fields by means of a conducting wire (stretched or vibrating) is the effect of background magnetic fields, e.g., the Earth magnetic field. For instance, a common way to compensate a background field for the vibrating-wire method is to work with the second resonance (at which the effect of uniform external fields cancels out) and place the magnet at L/4, where L is the wire length. However, if the background field is not homogeneous along the wire, this compensation scheme does not work and other solutions, such as rotating the magnet around the horizontal axis have to be adopted [10].

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In this paper, the compatibility of the magnetic centers localized by the stretched-wire method and the vibrating-wire methods for the same quadrupole, by using the same setup configuration is checked. The repeatability of the two methods is assessed at varying the magnetic field gradient. Furthermore, the effect of the background field on both the stretched-wire and vibrating-wire measurements is investigated.

2. BACKGROUND

2.1. Stretched-wire method

The stretched-wire method exploits the Faraday's induction law: when a single conducting wire is moved inside a magnetic field, the properties of this field are obtained by measuring the voltage induced across the wire. Suppose that the wire is moved in an ideal quadrupole field by displacing its ends co-directionally in the horizontal plane, i.e., first by a quantity $+d$ and then by $-d$ from an initial position (x_0, y_0). The integral field gradient can then be evaluated as

$$(gL_m)_x = \frac{\Phi(x_0, x_0 + d) - \Phi(x_0, x_0 - d)}{d^2}\,, \qquad (1)$$

where Φ is the measured magnetic flux, g is the magnetic field gradient, and L_m is the magnetic length. Measuring in one direction and then to the opposite allows the compensation of uniform external fields. The same applies for vertical displacements, unless a correction for the wire sagitta is required.

The magnetic center position (x_c, y_c), defined as the position where the first longitudinal field integral is zero can then be calculated from

$$\begin{aligned} x_c &= x_0 - \frac{d}{2}\frac{\Phi(x_0, x_0 + d) - \Phi(x_0, x_0 - d)}{\Phi(x_0, x_0 + d) + \Phi(x_0, x_0 - d)} \\ y_c &= y_0 - \frac{d}{2}\frac{\Phi(y_0, y_0 + d) - \Phi(y_0, y_0 - d)}{\Phi(y_0, y_0 + d) + \Phi(y_0, y_0 - d)}\,. \end{aligned} \qquad (2)$$

The magnetic tilt can be measured in a similar way by moving the wire ends in opposite directions (counter-directional movement) and determining the position where the second field integral is zero.

2.2. Vibrating-wire method

The vibrating-wire method consists of powering the wire with a sinusoidal current, such that the Lorentz force due to the current and the magnetic field determines mechanical vibrations in the wire. The measurement of vibration amplitude and phase allows the magnetic field along the wire to be reconstructed. The excitation-current frequency can be set to match the mechanical resonance condition in order to increase the sensitivity.

When the wire is excited in its resonance, the vibration can be described approximately as a function of time t and of the longitudinal coordinate z by the following equation

$$\begin{aligned} u(z,t) \approx \frac{I_0}{\rho\alpha\omega_m} \sin\left(\frac{m\pi}{L}z\right) \sin\left(\omega_m t - \frac{\pi}{2}\right) \\ \frac{2}{L}\int_0^L B_\mathrm{n} \sin\left(\frac{m\pi}{L}z\right) \mathrm{d}z \end{aligned} \qquad (3)$$

where I_0 is the amplitude of the excitation current, ρ is the mass density per unit length, α is the damping coefficient, ω_m is the m^th resonance frequency, T is the mechanical tension in the wire, L the length of the wire, and B_n is the component of the magnetic flux density, normal to the wire direction.

By positioning the magnet at the longitudinal center of the wire and measuring the wire vibrations by means of a pair of photo-transistors, the magnetic center is located when the vibration is zero for the first resonant mode. The offset from the wire initial position can be found by solving a zero-finding problem, i.e., find the wire position $\mathbf{X} = (x_A, y_A, x_B, y_B)$, the coordinates of its extremities, such that

$$(\delta_x(\mathbf{X}), \delta_y(\mathbf{X})) = \mathbf{0}\,, \qquad (4)$$

where $\delta = max_t(u(z_0, t))$. The magnet tilt angle can be determined by exciting the second resonant mode and accomplishing counter-directional movements of the wire.

The effect of uniform background fields is commonly compensated for by displacing the magnet along the wire at $L/4$ rather than $L/2$, and exciting the second and fourth modes, where the forcing terms due to homogeneous fields cancel out.

3. PERFORMANCE COMPARISON PROCEDURE

The compatibility of the stretched- and vibrating-wire measurements of the magnetic center is checked by adopting procedure described in the following. It is assumed that, because of co-directional wire movements, the wire position is unequivocally determined by the couple $(x, y) = (x_A, y_A) = (x_B, y_B)$. The procedure consists of the following steps:

- powering the magnet by a given DC current;
- positioning the wire at an initial position (x_0, y_0);
- performing a stretched-wire measurement of the magnetic center by measuring the quantities defined in eq. (2) and evaluating (x_c^{sw}, y_c^{sw});
- repositioning the wire back to (x_0, y_0);
- performing a vibrating-wire measurement of the magnetic center, by measuring the wire vibration amplitude at different positions for each axis and interpolating the measured vibration amplitudes in order to find the solution of problem (4);
- comparing the measured center in terms of compatibility and repeatability.

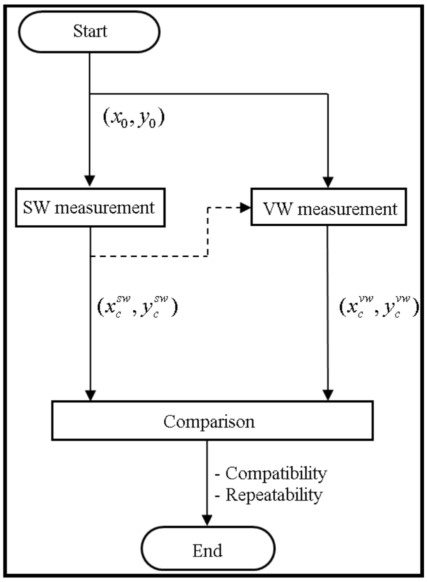

Fig. 1. Comparison procedure of stretched-wire and vibrating-wire method.

4. INFLUENCE OF THE BACKGROUND FIELD

In this section, the effect of background fields on the magnetic center measurement is discussed. This is done by assuming to deal with an ideal quadrupole, i.e., a linear rise of the magnetic field strength as a function of the distance from the center, and the linearity of the measurement system.

For the vibrating-wire method, an excitation frequency close to the first resonance is also assumed. Then, owing to the aforementioned assumptions, the vibration amplitude is given by the linear superposition of the quadrupole and the external field B^{E}, and using the model (3), one obtains

$$\delta_x(x,z) = \kappa(I_0,\omega,z)\int_0^L \left[g(z)(x-x_c) + B_y^{\mathrm{E}}(z)\right] \sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z\,, \quad (5)$$

where $\kappa(I_0,\omega,z)$ is the transfer function from the magnetic field to the local wire vibration, depending on the driving current amplitude and frequency. Therefore, the vibration amplitude is the sum of two contributions, one of which is depending on the magnetic strength, the other not. This will alter the location of the detected magnetic center, giving an apparent center, depending on the ratio between the background field strength and the magnet strength.

The same observations can be done for the stretched-wire measurements. Assuming in fact that the measured flux is the sum of two contributions, one arising from the magnet, $\Phi_g(x_0, x_0+d)$, and one from the background field, $\Phi_e(x_0, x_0+d)$, that is

$$\Phi'(x_0, x_0+d) = \Phi_g(x_0, x_0+d) + \Phi_e(x_0, x_0+d)\,, \quad (6)$$

the detected center will vary depending on the magnet strength.

5. EXPERIMENTAL RESULTS

5.1. Setup

The system used for the experiment is the same as described in [11], which can be used both for stretched-wire and vibrating-wire measurements. The measured magnet is a normal-conducting quadrupole magnet, which was constructed for the LEP machine at CERN (reference name ”LEP-LI-QS”). The magnet has an aperture of 10 cm and a length of 10 cm. The length of the wire was 1870 mm. The magnet was positioned in the longitudinal center of the wire.

For the stretched-wire measurement, a distance d of 10 mm was chosen for both horizontal and vertical wire displacements. For the vibrating wire, equidistant measurement points inside a range of ± 1 mm around the initial position (x_0, y_0) were fixed. The driving current amplitude was set to 50 mA, the frequency to 73.1 Hz, which is slightly below the resonance frequency, $f_1 = 73.7$ Hz, to minimize instabilities of the resonance condition [9]. The measurement was repeated also for different values of the magnet current.

For the investigation of background field effect on the vibrating-wire method the magnet was also moved to a longitudinal position $L/4$ from one of the wire ends and the second resonance was excited to find the center. The fundamental frequency was 74.46 Hz. The driving current frequency was set to 148.1 Hz and the amplitude to 50 mA.

5.2. Results

The center coordinates measured by the two methods at a magnet current of 10 A are shown in Tab. 1. The standard deviation was calculated for both methods over a set of ten measurement repetitions. For the vibrating-wire, according to aforementioned measurement procedure, the magnetic center was obtained by linear fitting of the measured vibration amplitudes as a function of the wire displacement. The results are compatible but the repeatability of the vibrating-wire measurement is at least two times better, owing to the high sensitivity arising from the resonance.

Table 1. Offset between magnetic center and wire initial position measured by the stretched-wire and vibrating-wire methods.

Method	x_c [μm]	σ_{x_c} [μm]	y_c [μm]	σ_{y_c} [μm]
Stretched	-203	29	48	15
Vibrating	-209	7	58	8

In a successive experiment with the same setup, the measurements were repeated at different magnet currents by assessing the repeatability of the methods as function of the magnet gradient (Fig. 2). The integral gradient values used for this estimation were measured by the stretched-wire method, according to formula (1). The repeatability of the stretched-wire method depends on the field strength and tends to approach the one of the vibrating-wire for values above 0.4 T.

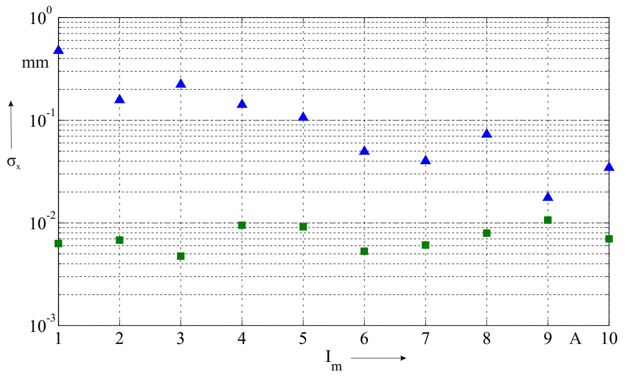

Fig. 2. Standard deviation of the measured center (x coordinate) by stretched-wire (blue triangles) and vibrating-wire (green squares) method as a function of the magnet gradient.

5.3. Background field influence

The apparent average centers measured at different magnet currents, also with inverted polarity, are shown in Fig. 3 for the vibrating wire. The deviation of the apparent center from the actual one increases as the magnet strength decreases and can be fractions of a millimeter. The actual center can be taken as the average of the measurement done at inverted polarities. For instance, the difference between the actual and the apparent center is 30 μm in x and 10 μm in y at 10 A magnet current.

The configuration where the magnet is positioned at $L/4$ was also studied. As the background field was not homogeneous along the wire, its effect was noticeable also; see Fig. 3 (c). The difference between the actual and the apparent centers is in this case 46 μm in x and 15 μm in y at 10 A magnet current, which is even slightly higher than for the first configuration. This can be attributed to the fringe-field generated by the stepper motor used for tensioning the wire. This fringe field is more effective on the second resonant mode, because it is located closely to one of the wire ends. This non-uniformity of the background field is compatible with previous observations carried out on the same system [12].

The measurement by stretched-wire method at different magnet gradients produced the results shown in Fig. 4. At 10 A the difference between the actual and the apparent center is 153 μm in x and 150 μm in y.

6. CONCLUSIONS

The stretched- and vibrating-wire methods were employed for measuring the magnetic center of a quadrupole test magnet at CERN. The compatibility of the two methods was demonstrated, and the repeatability was compared as a function of the magnetic field strength. It was shown that, for the given setup, with 0.3 T integral field gradient and 10 cm aperture, the repeatability of the vibrating-wire measurement is at least two times better than for the stretched wire.

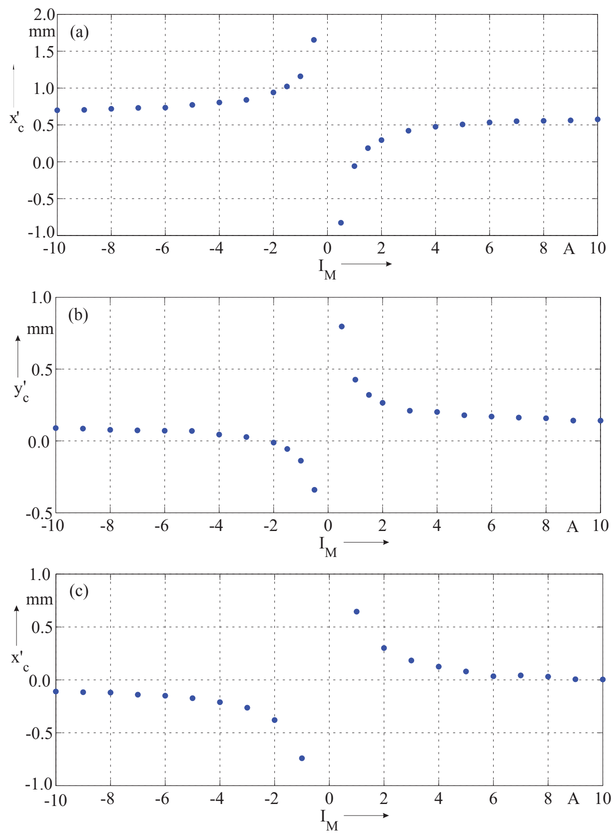

Fig. 3. Measured magnetic center by the vibrating wire as a function of the magnet current. (a) x coordinate measured with the magnet at $z_{\mathrm{M}} = L/2$; (b) y coordinate measured with the magnet at $z_{\mathrm{M}} = L/2$; (c) x coordinate measured with the magnet at $z_{\mathrm{M}} = L/4$ and second wire resonance.

Moreover, the influence of background fields on the measurement of magnetic centers was investigated. It was shown that such a field determines an apparent center that moves as a function of the magnet strength. The difference between apparent and actual centers was found to be 46 μm for the vibrating wire and 153 μm for the stretched wire, at 0.3 T integral field gradient. Furthermore, for the vibrating wire it was also shown that non-homogeneous distributions of the background field can occur, which invalidate the commonly used compensation scheme.

The discussed methods have a relevance within the Particle Accelerator Components Alignment and Metrology to the Nanometre scale project (PACMAN) [1][2], where a wire system will be used to measure the axis of the main-beam quadrupoles for the Compact Linear Collider (CLIC) [2].

[2]The PACMAN project is funded by the European Union's Seventh Framework Programme for research, technological development and demonstration.

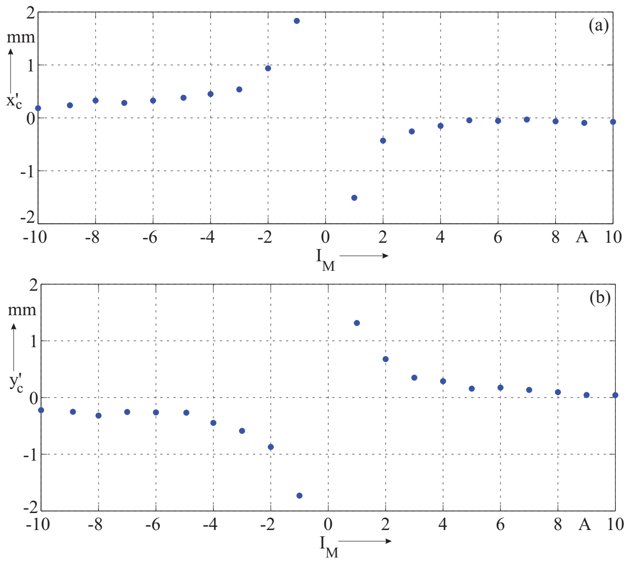

Fig. 4. Apparent magnetic center measured by the stretched wire as a function of the magnet current. (a) x coordinate; (b) y coordinate.

REFERENCES

[1] *PACMAN project's webpage*. URL: `http//cern.ch/pacman`.

[2] *The Compact Linear Accelerator's webpage*. URL: `http://clic-study.org/`.

[3] J. DiMarco, H. Glass, M. Lamm, P. Schlabach, C. Sylvester, J. Tompkins, and J. Krzywinski. "Field alignment of quadrupole magnets for the LHC interaction regions". In: *IEEE Transactions on Applied Superconductivity* 10 (Mar. 2000), pp. 127–130.

[4] Z. Wolf. *A Vibrating Wire System For Quadrupole Fiducialization*. Tech. rep. LCLS-TN-05-1. SLAC National Accelerator Laboratory, Menlo Park, California, USA, 2005.

[5] D. Zangrando and R. P. Walker. "A stretched wire system for accurate integrated magnetic field measurements in insertion devices". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 376 (2 July 1996), 275282.

[6] J. DiMarco J.and Krzywinski. *MTF Single Stretched Wire System*. Ed. by F. MTF. MTF-96-0001. 1996.

[7] A. B. Temnykh. "Vibrating wire field-measuring technique". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 399.2 (June 1997), pp. 185–194.

[8] L. Bottura, M. Buzio, S. Pauletta, and N. Smirnov. "Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments". In: *Instrumentation and Measurement Technology Conference, 2006. IMTC 2006. Proceedings of the IEEE*. 2006, pp. 765–770.

[9] C. Wouters, M. Calvi, V. Vrankovic, S. Sidorov, and S. Sanfilippo. "Vibrating Wire Technique and Phase Lock Loop for Finding the Magnetic Axis of Quadrupoles". In: *Applied Superconductivity, IEEE Transactions on* 22.3 (2012), pp. 9001404–9001404. ISSN: 1051-8223.

[10] Z. Wolf and M. Y. Levashov. *Set up and test results for a vibrating wire system for quadrupole fiducialization*. Tech. rep. LCLS-TN-06-14. SLAC National Accelerator Laboratory, Menlo Park, California, USA, 2005.

[11] P. Arpaia, C. Petrone, S. Russenschuck, and L. Walckiers. "Vibrating-wire measurement method for centering and alignment of solenoids". In: *Journal of Instrumentation* 8.P11006 (Nov. 2013).

[12] P. Arpaia, D. Caiazza, C. Petrone, and S. Russenschuck. "Challenges in measuring the longitudinal field profile of a magnet by a vibrating wire". In: *20th IMEKO TC-4 International Symposium, Proceedings*. Sept. 2014, pp. 822–826. ISBN: 978-92-990073-2-7.