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Helmholtz coils system for testing field meters used to measure magnetic fields generated by traction vehicles

***Abstract**. This paper presents a Helmholtz coils system for testing field meters used to measure magnetic fields generated by traction vehicles. The results of conducted studies of the levels of magnetic fields generated by electrical and electronic devices in the railway environment indicate the need for control tests of systems for measuring electromagnetic fields. The test stand developed for controlling magnetic field tests ensures the correctness, reliability, and repeatability of these tests.*

Streszczenie.** W artykule przedstawiono układ cewek Helmholtza zastosowany do testowania mierników pola stosowanych do pomiaru pól magnetycznych generowanych przez pojazdy trakcyjne. Wyniki przeprowadzonych badań poziomów pól magnetycznych generowanych przez urządzenia elektryczne i elektroniczne w środowisku kolejowym wskazują na konieczność przeprowadzania badań kontrolnych układów do pomiarów pól elektromagnetycznych. Opracowane stanowisko do kontroli pomiarów pola magnetycznego zapewnia poprawność, wiarygodność i powtarzalność tych badań. **(Układ cewek Helmholtza do testowania mierników pola stosowanych do pomiaru pól magnetycznych generowanych przez pojazdy trakcyjne)

Keywords: Helmholtz coils, electromagnetic field, traction vehicles, magnetic field measurement.
Słowa kluczowe: cewki Helmholtza, pole elektromagnetyczne, pojazdy trakcyjne, pomiar pola magnetycznego.

Introduction

In a railway environment, magnetic field testing is required. Measurement of the magnetic field level is performed in accordance with the requirements of the standard PN-EN 50500 [1]. The scope of the test covers frequencies from 0 to 20 kHz. The measuring tools used to measure fields should be calibrated, which requires the generation of a standard magnetic field. One of the most suitable methods for generating homogeneous magnetic fields is to use the Helmholtz coil system. They are widely used to produce uniform magnetic fields [2,3,4]. Helmholtz coils are used in scientific, engineering, and industrial applications that require uniform magnetic fields. Helmholtz coils are commonly used in laboratories to generate known uniform magnetic fields for testing and calibration of magnetic sensors, magnetometers, and other magnetic field measurement instruments [5,6]. They are also used for electromagnetic compatibility tests to generate uniform magnetic fields to test electronic devices and systems, as well as for medical and many other applications [7,8].

The railway environment is exposed to electromagnetic fields generated by railway power systems, rolling stock, and nearby transmission lines. To ensure the correctness, reliability, and repeatability of magnetic field level tests, it is necessary to constantly monitor the measurement tools used. The need to conduct inspections of this type of tests also results from the provisions of the PN-EN-ISO/IEC 17025 standard [9], the application of which is obligatory in accredited laboratories. For this reason, a test stand based on Helmholtz coils was designed for a uniform magnetic field. The constructed measuring stand was used to test selected magnetic field analyzers. This paper presents the results of the magnetic flux density measurements *B* in the Helmholtz coil system under laboratory conditions. In addition, the article presents the analysis and results of measurements of magnetic fields generated by traction vehicles such as a tram, an electric multiple units, and a locomotive with a diesel engine by using a selected magnetic field analyzer. The methodology for measuring magnetic fields on rolling stock, together with the criteria for evaluating the results, is presented in [10]. Measurements were made in accordance with current standards and regulations.

Helmholtz coils system - requirements

The goal of this project was to build a magnetic field measurement control stand that would meet normative requirements and allow for reasonably comfortable testing under field conditions. The requirements for the designed device are defined on the basis of PN-EN 50500 [1], that is, it was assumed that: generation of a magnetic field with a frequency of 1 Hz ÷ 20 kHz; the size of the coils to allow inside the probe with three mutually perpendicular loops with a cross-sectional area of 100 cm^2 each; value of flux density B > 0.5 μT. The stand was assumed to operate at positive temperatures of 5 ÷ 40°C with moderate humidity. For this reason, the selection of the system components and its electronic components did not require special consideration for protection against excessive humidity or extreme temperatures.

The main component of the developed stand is the Helmholtz coils system (see Fig. 1). Helmholtz coils were originally built to compensate for the Earth's magnetic field.

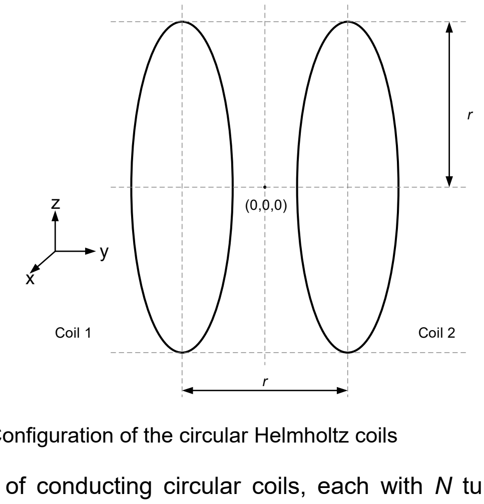

Fig. 1 Configuration of the circular Helmholtz coils

A pair of conducting circular coils, each with N turns and each carrying a current I, separated by a distance equal to the radius r of the circular loops, produces a homogeneous magnetic field B in the median plane between the two circular coils.

Helmholtz coils - mathematical model and numerical simulation

The mathematical model is based on the differential elements of the magnetic fields expressed by the Biot–Savart law. According to the law of Biot-Savart, the diameter of the coil and its distance are proportional to the size of the magnetic field that we need to produce. The magnetic flux density on the circular coil axis is calculated by superposition of the contributions of each coil [11,12]. Therefore, the expression of the magnetic field at a point of the symmetry axis and at a distance y can be written as:

$$(1)\quad B(y) = \frac{\mu_0 N I r^2}{2}\left\{\left[r^2 + \left(y + \frac{r}{2}\right)^2\right]^{-\frac{3}{2}} + \left[r^2 + \left(y - \frac{r}{2}\right)^2\right]^{-\frac{3}{2}}\right\}$$

where μ_0 is permeability of free space, I is the coil current [A], N is the number of turns of each coil, r is the radius of the coil [m], y is the distance of the point on the Y axis from the centre point between the coils, [m].

Equation (1) is only applicable to infinitely thin coils. The default assumption is that each subcoil is infinitely thin, so that the cross section of the wire bundle is much smaller than the diameter of the coil [12].

At the geometric centre of the Helmholtz coil (y=0), the magnetic flux density is [11]:

$$(2)\quad B(0) = \left(\frac{4}{5}\right)^{\frac{3}{2}} . \mu_0 . \frac{NI}{r} \quad [\mathrm{T}]$$

Based on a mathematical model, numerical simulations were conducted to evaluate the final design of the coils. These simulations were performed considering the real configuration of the system. The computational system of Helmholtz coils is shown in Fig. 2. To analyse the distribution and uniformity of the magnetic field in the Helmholtz coils system, a 3D model was developed in Comsol software.

The simulation results verified the uniformity of the magnetic field. A uniform field generated by Helmholtz coils was obtained over the required area (see Fig. 2).

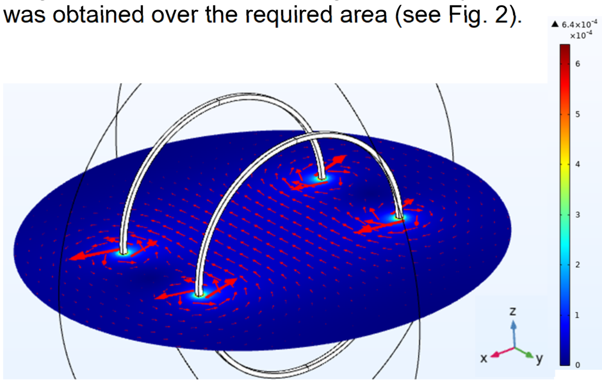

Fig. 2 Contour map of magnetic flux density of the Helmholtz coils

The magnetic field uniformity factor (δ) has been defined by the following expression,

$$(3)\quad \delta = \frac{B_i - B_0}{B_0} \cdot 100\%$$

where B_i is the magnetic flux density at any point within the volume, B_0 is the magnetic flux density at the centre of the coils.

The computational magnetic field uniformity was performed by plotting a distribution of the radial magnetic flux density for an axial position B(y) within the coils – Figure 3.

Figure 4 shows a graph of the uniformity of the magnetic field δ by the formula (3), where the values of the coordinates of the y-axis are given by the radius of the coil r. Looking at Figure 4, it can be seen that at a point 0.25·r away from the center of the system along the Y axis, the deviation from uniformity with respect to the magnetic flux density at the centre point of the system is less than 0.5% (shown by the dashed line in Fig. 4), and at a point 0.38·r from the center of the system is less than 2%, and finally in the entire range between the coils δ < 5%. The value of the magnetic field uniformity coefficient is sufficient for our application.

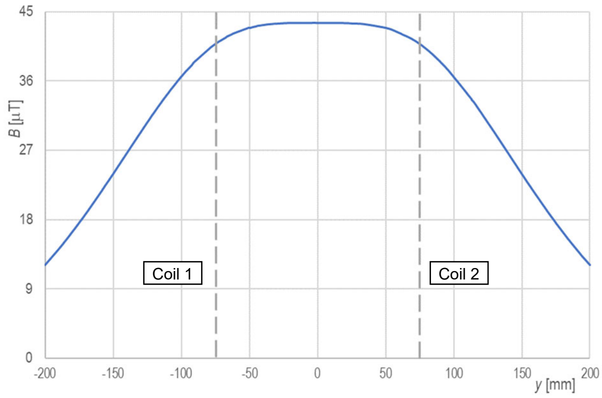

Fig. 3 Radial magnetic flux density distribution for an axial position between the coils of the computational model

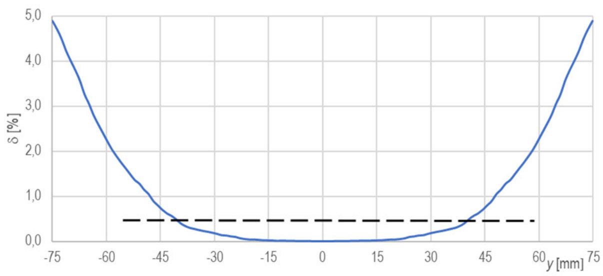

Fig. 4 The magnetic field uniformity factor (δ) in the Helmholtz coils system

Helmholtz coils - system manufacturing

A prototype was manufactured on the basis of numerical simulation results. The diameter size of the coils was set at 300 mm. The coil support is made of 5 mm thick polymethyl methacrylate (PMMA). The circular PMMA frame is designed with locking screws to connect the coils and hold them in place, allowing the system to be positioned correctly as shown in Fig.5. The copper wires of 0.75 mm in diameter (21 AWG) were wound by hand. The circular-shaped coil has 15 numbers of turns in each loop. The two windings are connected in series, so the current flowing through the coils is the same and in the same direction. Furthermore, to regulate the current that flows through the coils, two resistors with a resistance value of 33 Ω were used. In parallel connection, the resultant resistance was obtained with a value of 16.5 Ω and a power of 100 W. The system is mobile because it is installed on a rack, which makes it easy to transport and use in various locations. The main design goal was to build a test stand for measuring magnetic fields that could be used in both laboratory and real-world conditions.

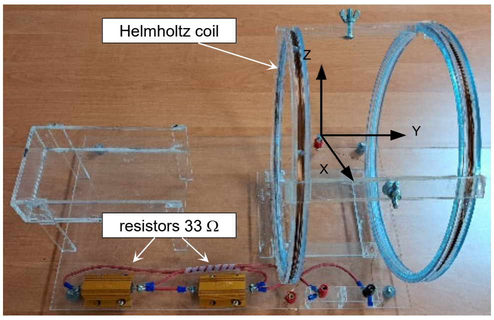

Fig. 5 Coil system during preparation for testing

Schematic block diagram of the measuring setup is shown in Figure 6.

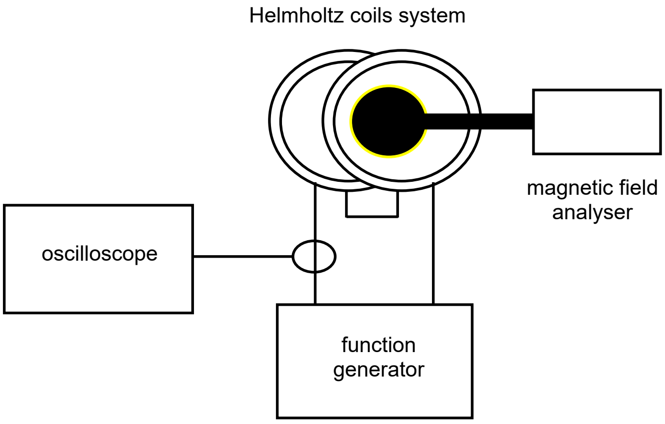

Fig. 6 Schematic block diagram of the measuring setup

Figure 7 shows the constructed Helmholtz coils system along with the measurement system to test the correctness of the magnetic field meters. A JC5620P function generator was used as the source of the test signal with power output. The generator power output parameters are the output frequency from 0.1 Hz to 100 kHz, the maximum power output voltage 50 Vp-p, and the maximum power output current 1 Ap-p. The current flowing through the coil was measured using AC/DC current probe type A622 manufactured by Tektronix. The parameters characterizing the coils were measured using an RLC bridge.

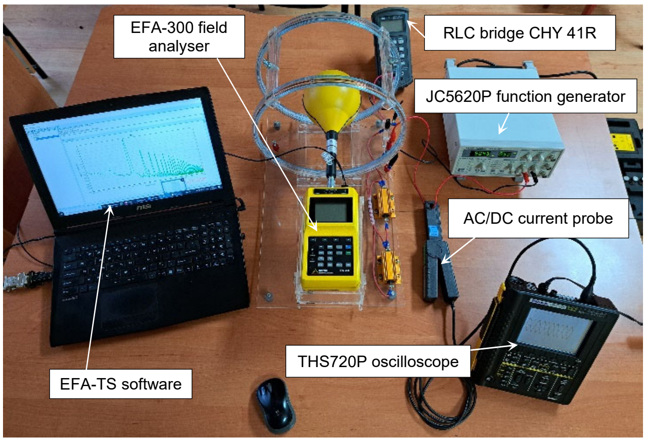

Fig. 7 Experimental setup and equipment for Helmholtz coils test

The built test rig was used to test a selection of magnetic field analysers. One of the EFA-300 field analysers tested with EFA-TS software is shown in Figure 7.

Results - research and measurements

Firstly, the magnetic field levels in the Helmholtz coil system were investigated under laboratory conditions. In the system shown in Fig. 7, magnetic flux density values were measured using a three magnetic field meters: EFA-300 (manufactured by NARDA), ESM-100 (manufactured by Maschek Elektronik) and SMP2 (manufactured by Wavecontrol). During the tests, the magnetic field meter probe was placed at the central point of the space between the coils (see Fig. 7 and 8).

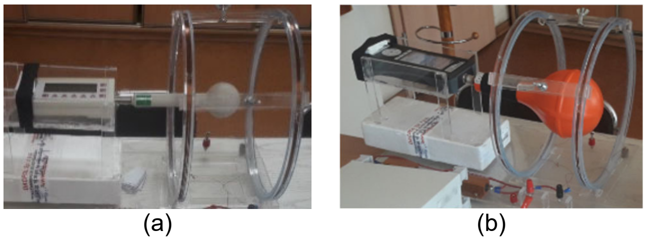

Fig. 8 A tested magnetic field meters: (a) ESM-100 (manufactured by Maschek Elektronik); (b) SMP2 (manufactured by Wavecontrol)

Measurements were made for selected generated frequencies at a constant voltage 10 Vp-p. The results of the selected trials are included in Table 1 and graphically interpreted in Fig. 9. The differences between the generated and recorded frequencies are within the error limits.

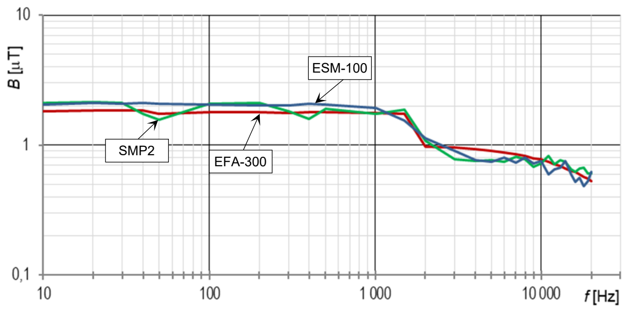

Fig. 9 Magnetic flux density as a function of the frequency of the generated signal

Table 1. Measurement results of magnetic flux density values

Lp.	Generator frequency	Frequency recorded	Flux density (EFA-300)	Flux density (SMP2)	Flux density (ESM-100)
	[Hz]	[Hz]	[µT]	[µT]	[µT]
1	5,001	4,894	1,744	1,975	1,95
2	10,02	10,014	1,830	2,121	2,05
3	50,0	49,998	1,752	1,560	2,09
4	100,1	100,13	1,781	2,094	2,05
5	500,3	500,4	1,786	1,915	2,05
6	1001,5	1005,2	1,768	1,746	1,93
7	5002,0	5001,7	0,909	0,764	0,75
8	10004	10006	0,780	0,722	0,76
9	15046	15047	0,634	0,655	0,60
10	20008	20009	0,530	0,606	0,62

Figures 10 and 11 show the results of the FFT analysis for the selected frequencies. Analysing the results obtained in Table 1 and shown in Figures 9 ÷ 11, it can be concluded that the performance of the system is correct and that it is suitable for use in the test control. Each time, the obtained magnetic field measurement result was several orders higher than the measured background value for the same frequency. Over the entire required frequency range of the magnetic field measurement, the test signal is unambiguously traceable and allows confirmation of the correct operation of the magnetic field meter.

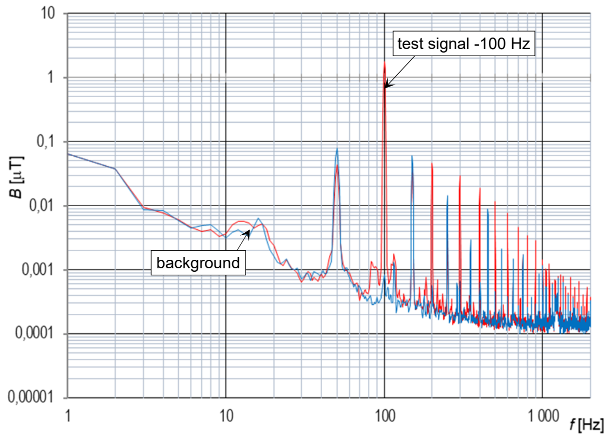

Fig. 10 Magnetic field level - 100 Hz signal

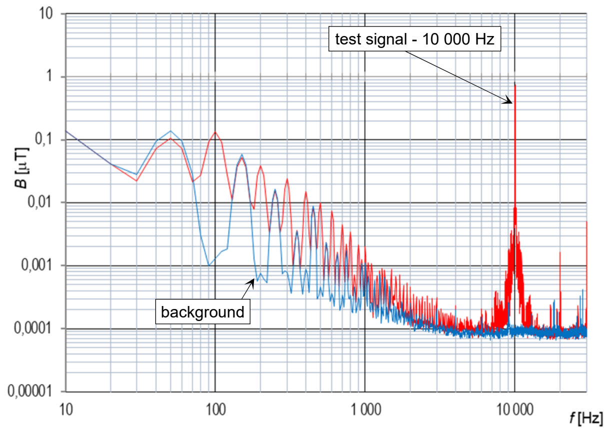

Fig. 11 Magnetic field level – 10 000 Hz signal

Selected results of magnetic field measurement

To measure the magnetic fields generated by the traction vehicles, the EFA-300 field analyser was used. The results of magnetic field measurements in three mutually perpendicular directions in the 1 Hz ÷ 32 kHz band are shown in Fig. 12-14 as the result of the FFT spectrum analysis. Figures 12-14 also shows the permissible levels of the magnetic field in the frequency band 1 Hz ÷ 30 kHz specified in the ICNIRP document [13], in Directive 2013/35/EU [14] and in the Regulation of the Ministry of Labour and Social Policy [15].

The following descriptions have been used in the Fig. 12-14, referring to the fulfillment of the criterion of the level of the permissible magnetic field, taking into account the measurement uncertainty of this field (if such cases occur):

1. Exceeding the permissible levels is marked with pink rectangles, described in the legend "B - U_{lab} (B) > Limit B".
2. Frequency bands for which the criteria of conditional compliance with a probability of 50% were applied are marked with blue rectangles, described in the legend "B + U_{lab} (B)".
3. Frequency bands for which the criteria of conditional non-compliance with a probability of 50% were applied are marked with orange rectangles, described in the legend "B - Ulab (B)".

The values of the expanded measurement uncertainty U_{lab} (B) has been determined as the standard uncertainty of measurement multiplied by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95%.

The magnetic field level was measured in the driver's cabin. The measurements in the cabins were made at a height of 0.9 m and 1.5 m from the floor. The results obtained suggest incorrect operation of the meter or incorrect measurement. Usually, for measurements at the same point at different heights, different values of the magnetic field are obtained, but their nature is similar [10]. The measurements were repeated, and correct results were obtained, which is why it is so important to check the field measurement meters.

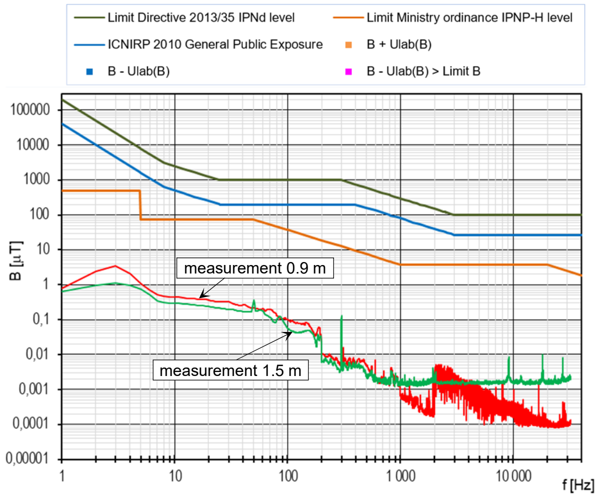

Fig. 12 Magnetic field level in the train driver cabin of an electric multiple unit - incorrect results

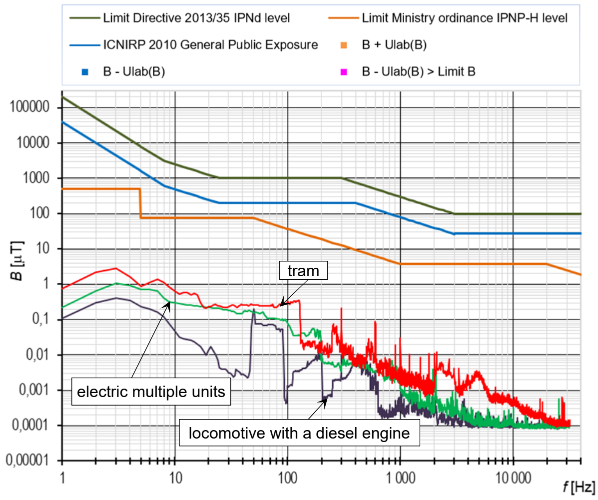

Fig. 13 Magnetic field level in the driver's cabin in various vehicles

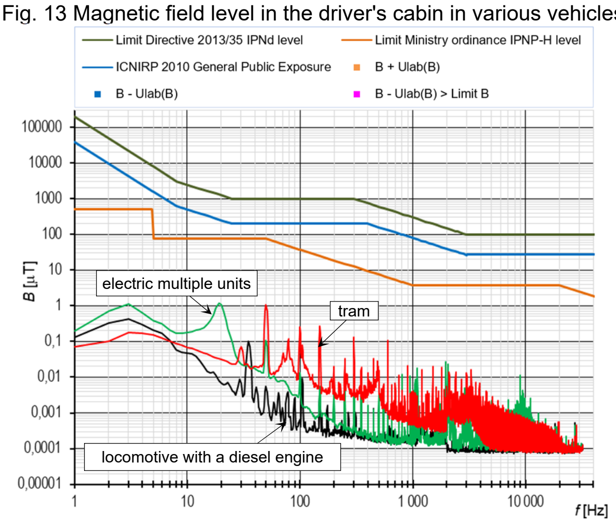

Fig. 14 Magnetic field outside vehicles

Moreover, measurements of magnetic fields generated by traction vehicles such as trams, electric multiple units, and locomotive with a diesel engine were carried out. Measurements were made in accordance with applicable standards and regulations. Figures 13 and 14 show the results obtained for measurements in driver's cabins and outside vehicles, respectively.

The values of the magnetic field levels are lower than the permissible values and meet the requirements, but it can be noted that the highest levels of magnetic field intensity were obtained during the tram test.

Conclusions

The paper demonstrates the importance of calibration control of electromagnetic field measuring instruments. A test rig was developed for the control testing of electromagnetic field measurement systems. On the basis of the tests carried out, it was found that the system works properly and is suitable for controlling magnetic field tests in the railway environment. Moreover, it was noticed that among the tested traction vehicles, trams achieved the highest levels of magnetic field intensity, which was already indicated in the authors' previous works.

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