Investigation of the influence of a large steel plate on the magnetic field distribution of a magnetic proximity detection system

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Abstract

A magnetic proximity detection system is mounted on a mobile mining machine to prevent underground workers from being pinned or struck by machine motion. The system generates magnetic fields around the machine to determine safe working distances. The miner-worn component measures the magnetic field in order to approximate location. Large masses of steel, such as those from mining equipment, can alter the magnetic field distribution. This affects the locational accuracy of the system, thus adversely impacting worker safety. To examine this problem, U.S. National Institute for Occupational Safety and Health researchers developed a method and test system to study the influence of a steel mass on the magnetic field distribution. The results show that a steel plate can strengthen the magnetic field perpendicular to the generator by up to 40 percent. Furthermore, they show that the degree of the influence on the field distribution is a function of distance. The results from this study can be used to further develop and improve the performance and reliability of electromagnetic proximity detection systems used in underground mining applications.

Introduction

On average, 250 miners are injured every year, and 43 miners were reported to be killed by striking or pinning accidents involving continuous mining machines in the United States between 1984 and 2015, according to the U.S. Mine Safety and Health Administration (MSHA, 2015). Continuous mining machines are large mobile machines used to mechanically cut coal in underground mines. These machines weigh approximately 60 t (132,000 lb) each. Although modern continuous mining machines can be remotely controlled, operators still need to be close to the machine primarily because of the low visibility and wide blind spots of the underground working environment.

The MSHA promulgated a final regulation in 2015 that requires the use of proximity detection systems on all continuous mining machines except full-face machines. MSHA has

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approved five such systems to be intrinsically safe for use in underground coal mines: (1) Strata Worldwide's HazardAvert System, (2) Frederick Mining's Model 200 HazardAvert Detection System, (3) Nautilus International's Coal-Buddy System, (4) Matrix Design Group's M3-1000/Joy Global SmartZone Gen 1 and (5) Matrix Design Group's IntelliZone/Joy Global SmartZone Gen 2.

The first four systems are mounted on continuous mining machines, and continuously generate a modulated low-frequency magnetic field, of around 100 kHz or lower, from generators covering the extended space around the continuous mining machine. A miner-worn component worn by personnel working in the vicinity of the continuous mining machine detects the magnetic flux density, B. With B and a known magnetic field distribution model, the proximity detection system can estimate the location of personnel relative to the machine (Li, Carr and Jobes, 2012). When a miner is detected at an unsafe distance relative to the continuous mining machine, the system generates a warning signal and disables the machine before it makes contact with the person wearing the miner-worn component. The fifth system uses a reverse technology with the miner-worn device generating the magnetic field and the magnetic sensors on the continuous mining machine detecting the magnetic flux density.

All proximity detection systems in use rely on a magnetic flux density distribution model to determine proximity between miner and machine. The model provides a relationship between distances from the generator and a magnetic flux density measurement. The model's accuracy for a given field is thus essential to determine the system's accuracy.

Research on proximity detection

Research on proximity detection for underground mining machines started in mid-2000, when U.S. National Institute for Occupational Safety and Health (NIOSH) researchers developed and tested prototypes of low-frequency magnetic proximity detection systems for continuous mining machines (Schiffbauer, 2002; Ruff, 2010). Several companies then developed commercialized products. To improve the accuracy and performance of proximity detection systems, other NIOSH researchers recently developed an intelligent proximity detection system, or iPD (Jobes and Carr, 2010), which uses a more accurate magnetic flux density distribution model called the shell-based magnetic flux density model, and a triangulation technique to more accurately determine miner locations around a continuous mining machine.

Shell-based magnetic flux density distribution model

A shell is defined as a collection of all of the points around the generator that have the equal magnetic flux density. These points collectively form an enclosure appearing as a shell. A spatial shell-based magnetic flux density distribution model for a field in a medium with a uniform permeability is graphically illustrated in Fig. 1, with the generator in the center (Li, Carr and Jobes, 2012). In this three-dimensional model, each shell has a geometrically symmetrical shape that is dependent on the distance away from the generator. The graph was created with measurements from the field generated from the generator, which consists of a coil of 136 turns on a ferrite core measuring $2.54 \times 2.54 \times 30.48$ cm ($1 \times 1 \times 12$ in.). The

model also defines the relationship of a distance between any point in a given shell and the center of the generator. The distance changes with location of a point in a shell.

The magnetic field distribution model can also be expressed in a two-dimensional form (Li, Carr and Jobes, 2012). Because the two-dimensional form shares the same model parameters and can adequately support the analysis in this study, it will be used as an analytical tool in this study.

The generator produces a magnetic *B*-field around it as an electric current flows through it (Fig 2). The solid curve shows the model of a magnetic shell. In a uniform-permeability medium, the closer to the generator, the stronger the field or the greater the *B* value is and the smaller the shell is. Because the model defines the relationship between the size and shape of a shell and the magnetic flux density, *B*, it was used in past research to determine the location of a miner in a multigenerator system through trilateration and other localization technologies. Using the magnetic flux densities for the fields generated by two or more generators mounted at different places on a machine and measured by a miner-worn component worn by a miner, the system can generate the models of the two or more corresponding shells. The intersection point of these shells is the estimate of the location of the miner-worn component (Li, Carr and Jobes, 2012; Li, Jobes and Carr, 2013; Carr, Jobes and Li, 2010).

A shell is obtained from the sum of two variable components: (1) a circle of radius *r* and (2) an offset *a* (Fig. 2). The *r* determines the basic size of the shell, while the *a*, which can be either positive or negative, modifies the shell from the circle. The NIOSH-developed model shows how the values of *r* and *a* change with changing values of *B* as well as with the angular position around the generator. This variation is described by a set of four constant model parameters: c_r, d_r, c_a and d_a. The c_r and d_r determine a variation for *r*, and the c_a and d_a for *a*. Importantly, the NIOSH researchers found that a magnetic field possesses its own unique set of these model parameters, and any change of them indicates a field distribution change (Li, Carr and Jobes, 2012; Li et al., 2013). This suggests that a difference of two magnetic fields can be identified by comparing their corresponding model parameters.

The shell-based model has found an application in determining the influence of an object on the magnetic field distribution. Such an influence can be identified and quantitatively analyzed through a comparison of the field model constant parameters, c_r s, d_r s, c_a s and d_a s between the magnetic models generated from measurements with and without the presence of the object. NIOSH researchers developed a methodology and an experimental system based on this principle to systematically measure the influence of in situ massive coal and rock strata in a coal mine on the magnetic field distribution of the system. The results showed that the parameters in the model, obtained with the presence of coal and rock, demonstrated small variations from the corresponding ones from the model, which were obtained with the absence of coal and rock. NIOSH researchers thus concluded that the massive in situ coal and rock had an insignificant influence on the magnetic field distribution of the proximity system. The model without the presence of coal and rock was obtained on the ground surface in this experiment (Li et al., 2013). A theoretical explanation for this

conclusion is that the coal and rock strata are not composed of magnetic material that is able to exert a notable influence on the field distribution.

In the present work, the same principle is used to study the influence of a large steel plate on the magnetic field distribution of a laboratory magnetic detection system.

Experimental method

Compared with coal and rock strata, steel is considered to be both a good magnetic and conductive material. It can therefore affect the field distribution. To examine the influence of steel, two magnetic field distribution models were obtained from two experimental setups, one with and one without a large steel plate placed near the generator. These models are compared to identify the variation in the field when a steel plate is introduced.

Experimental setup with no steel plate present

A generator, a magnetic probe and a plane polar measurement co-ordinate system were positioned on a 1.22×2.44 m (4 by 8 ft) wooden table elevated 1 m (3.3 ft) from the ground (Fig. 3). The ferrite-cored generator with core dimensions of 25.4×190.5 mm (1×7.5 in.) sat in the origin of the coordinate system along the x-axis. The generator had a matched capacitor that made the generator circuit resonate at the system operating frequency of 73.6 kHz. The IDR-200 magnetic probe provided the reading of magnitude of B field at a given point around the space of the generator. The coordinates of a point were determined from the plane polar coordinate system. The magnitude of a B reading was determined from the vector sum of the three magnetic flux components, x, y and z. The generator was powered by an Electronics & Innovation 2010L RF amplifier, and the amplifier was controlled with an Agilent 33220A signal generator. A constant current of 3.859 A flowing from the amplifier to the generator was maintained throughout the measurement stage.

A total of 495 measurements at different points around the generator were collected. Each point included a B reading and corresponding position coordinates. These points belong to 15 half-shells. Each of the half-shells had 33 different points. Figure 4 shows a sample plot of a half-shell generated from one set of 33 measurements with $B = 110.9$ mG. The shell components were $r = 352.67$ mm and $a = 49.54$ mm in this shell. With all of the 15 shell functions determined from the measurements of these 495 points, the field distribution model was then obtained from procedures described in Li, Carr and Jobes (2012), and given in Table 1 for the values of the magnetic field model parameters of c_r, d_r, c_a and d_a.

Experimental setup with steel plate present

The only difference with the previous setup was that an AISI 1020 steel plate measuring $122 \times 244 \times 0.635$ cm ($48 \times 96 \times 0.25$ in.) was placed next to the generator (Fig. 5). The electrical resistivity of the steel was approximately 1.0×10^{-7} Ω·m, compared with 200 to 2,000 Ω·m for coal, and the relative magnetic permeability was about 150, compared with 1 for air (National Physical Laboratory at Kaye & Laby, 2017; Field Precision LLC, 2017; Johnson, 2003). The plate was placed with one of its large surfaces parallel to the longitudinal axis of the generator. The generator was positioned 6 cm (2.4 in.) away from the center of the plate's surface. This was done to represent a gap typically found between a

generator of a commercialized proximity detection system and the steel body of a continuous mining machine. The polar coordinate system that sat on the wooden table was set to be perpendicular to the steel plate.

Similar to the experiment without the steel plate, a total of 495 points forming 15 different shells were measured. Each shell had the measurements of 33 points. As an example, a half-shell obtained in the experiment is shown in Fig. 6 with $B = 176.9$ mG, $r = 330.62$ mm and $a = 60.05$ mm. With the 15 shell functions determined, the field distribution model was obtained and given in Table 1 for the values of the magnetic field model parameters of c_r, d_r, c_a and d_a.

As shown in Table 1, the values of the model parameters c_r, d_r, c_a and d_a of the field with the steel present are significantly greater than the corresponding ones without the steel present. As previously stated, these parameters uniquely determine the distribution of a magnetic field, and the comparison of these parameters suggests that the steel plate significantly altered the field distribution.

The steel plate causes c_r and c_a, which are the model parameters used to determine the magnitudes of r and a, both of which are in millimeters, to increase by 48.2 and 30.2 percent, respectively. This suggests that the steel plate greatly strengthens the field in front of it. The steel plate also causes the d_r and d_a, which are the model parameters used to determine changes of r and a with B, to increase by 42.8 and 9.91 percent, respectively. This suggests that the steel plate causes a greater increase in magnitude of both r and a with a decrease of B. Figures 7a for r and 7b for a compare the changes in r and a of both fields resulting from their corresponding field model parameters. The results suggest that the lower B is or the farther the distance from the generator, the greater is the difference between the shell with the steel present and the shell without the steel present. This suggests that the degree of an actual magnetic field enhancement by the steel plate is a function of distance.

Figure 8a provides a comparison of two front half-shells near the generator at $B = 250$ mG: one with the steel plate absent and the other with it present. Similarly, Fig. 8b gives the two other front half-shells obtained with and without the steel plate at $B = 10$ mG. It is not difficult to determine that the degree of the shell enhancements by the steel plate vary with B or distance from the generator. The lower a B measurement is, as shown in Fig. 8b, or the greater the distance from the generator, the greater the enlargement of the shell by the steel plate becomes. This is because of a faster increase of both variables r and a of a shell with a decrease of B with the steel plate present.

Influence of steel on generator electrical parameters

Change of a generator impedance with change of distance between the generator and steel plate

According to Ampere's Law, the magnetic field flux density from a generator changes with respect to current flowing through it (Griffiths, 1999). To maintain a steady magnetic field, a magnetic proximity detection system needs to run with a steady current. An unexpected variation of the electrical parameter, especially as it relates to the impedance, can result in a

corresponding change of the generator current. A current change will, in turn, cause the magnetic flux density to change in the space around the generator, which can potentially result in a location measurement error.

The impedance of a generator is primarily determined by its inductance and resistance. For a generator using a capacitor to construct a resonant circuit, a change of the inductance of the generator can also cause a change in the impedance of the entire generator circuit. This will result in a change of the generator current and the magnetic flux density.

To understand the influence of the steel plate on the impedance of the generator used in the experiment, an Agilent E4980A LCR meter was used to measure its inductance and resistance at the operating frequency of 73.6 kHz (Fig. 9). In this experiment, the plate surface and generator were set in parallel, and the generator was moved toward the plate at equal distance intervals. The measurements show that the steel plate notably altered both the inductance and resistance of the generator within a distance of 200 mm (8 in.).

Figure 10a shows the measured inductance of the generator as a function of distance. The inductance clearly declines as the distance decreases. The resistance, on the other hand, increases as distance decreases (Fig. 10b).

The generator used a matched capacitor to maintain the generator circuit to resonate at 73.6 kHz with the absence of the steel plate. The test showed that as a result of the change in inductance after the steel plate was introduced with the gap distance of 6 cm (2.4 in.) from the generator, the resonant frequency of the generator circuit changed to 75.66 kHz with the originally matched capacitance. After the capacitor was replaced with the one with the rematched capacitance to bring the resonant frequency back to 73.6 kHz, the real power consumption of the system was found to be increased by 10 W with the same supply current. This increase was primarily due to the resistance increase of the generator circuit. This additional power consumption suggests that electrical power dissipated by the steel of a mobile mining machine needs to be taken into account when designing a system amplifier for a proximity detection system.

Electrically, the generator and the steel plate can be modeled as a transformer. The generator acts as the primary winding of the transformer, and the steel plate as the secondary winding. A voltage is induced in the steel plate, which produces the eddy current in the steel body that is responsible for turning the electrical energy to heat. The closer the steel plate is to the generator, the higher is the induced voltage. As a result, the eddy current will change accordingly. The eddy current change causes the corresponding change to the electrical energy consumed by the steel plate.

Discussion

The magnetic field distribution model parameters obtained in this study show that the steel plate strengthens the magnetic field in front of it. The measurements also show that the steel plate alters the impedance of the generator at a close distance between them. These changes can be attributed to the intrinsic magnetic and electrical properties of steel. Because of a variation of magnetic and electrical properties of steel, the influence of one type of steel on

the magnetic field distribution and generator circuit can be different from another. The quantifiable influence of a given type of steel on the magnetic distribution and the generator circuit can be determined with the experiment and modeling method introduced in this paper. The results and conclusions from this investigation can serve as a reference for general understanding of the influence of the steel.

The changes of inductance in the generator circuit under the influence of the steel plate suggest that to maintain good performance of those proximity detection systems that use a capacitor to make the generator circuit resonate with the system operating frequency, rematching of capacitance needs to be considered in order for the generator circuit to always retain resonance with the system operating frequency. Alternatively, the resonating frequency needs to be changed to keep up to the inductance changes of the generator when moved close to a steel mass. A poorly tuned generator circuit can result in a reduced generator current, a lower magnetic flux density, and a lower system efficiency, resulting in a lower performance of a system.

This paper presents the quantitative analysis of the influence of a large steel plate on the magnetic field distribution of the laboratory proximity detection system using only one setup, with the plane coordinate system positioned perpendicular to the steel plate. There can be many other setups, such as one in which the steel plate and the plane coordinate system are set at an angle other than 90°. In such cases, the method, data modeling process and analysis procedures introduced in this paper can be used to obtain a plane field distribution model. The model parameters obtained in this investigation can serve as a baseline for understanding magnetic field distribution under the influence of a steel plate.

The method, data modeling process and analysis procedures presented here can also be used for the field behind the plate. Our sample measurements showed that the magnetic flux densities over the space behind the plate were significantly lower than those in front of the plate, suggesting that the steel plate significantly weakened the field behind it. This is primarily attributed to the shield effect of the steel. This also suggests that the distribution model of the magnetic field behind the plate can be significantly different from the one in front of it, and a single symmetrical spatial model given in Fig. 1 can no longer adequately describe the fields separated by a steel plate. Further, this study shows that the two-dimensional model given in Fig. 2 can still hold and be used to model a plane field distribution. The difference of the fields separated by the steel plate implies that a more accurate field model needs to include at least two submodels: one for the field distribution in front of the steel, and the other for that behind the plate.

Conclusions

The paper introduces a method to systematically and quantitatively evaluate the influence of a large steel plate on the magnetic field distribution of a laboratory magnetic proximity detection system. Test results show the plate can significantly enhance the magnetic field in front of the plate and lower the field behind it. Such an uneven magnetic distribution results in a field that can no longer be adequately described by a perfectly symmetrical distribution model, but requires at least two submodels for each field divided by the plate.

The investigation also extends to evaluate the influence of the steel plate on the electrical impedance of the generator circuit. The results show the inductance and resistance of the generator can change notably when a steel plate is close to it. These findings can be used to ensure more accurate modeling of the magnetic field distribution and design of a proximity detection system generator circuit, resulting in more accurate worker location and improving system performance. Better performance of the proximity detection system can make mobile mining machines safer to operate.

Acknowledgments

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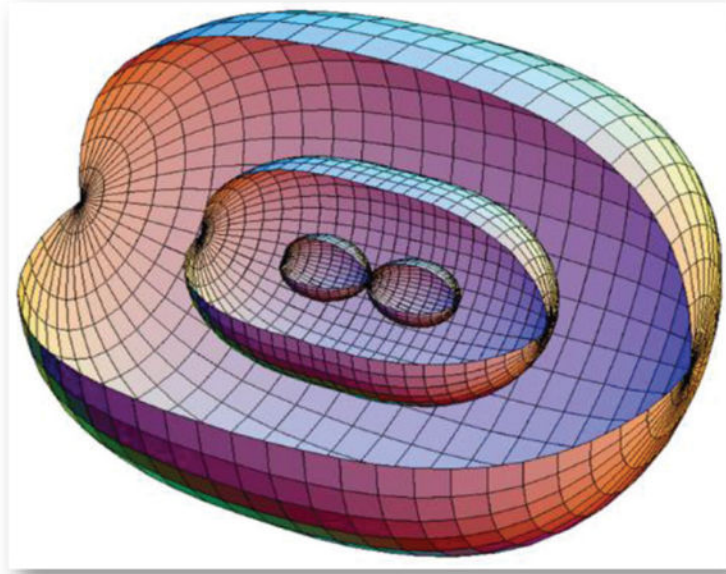
Figure 1.
Graphic presentation of a shell-based magnetic flux density distribution model with a generator in the center (generator not pictured).
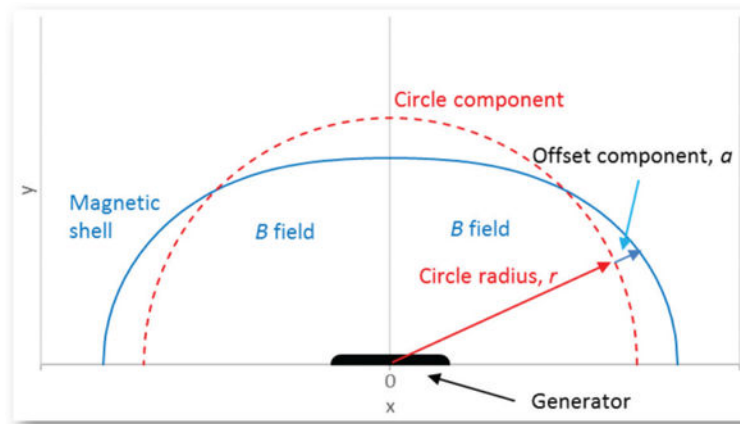
Figure 2.
A modeled two-dimensional magnetic shell is described with (1) a radius for a circle and (2) an offset from that radius.
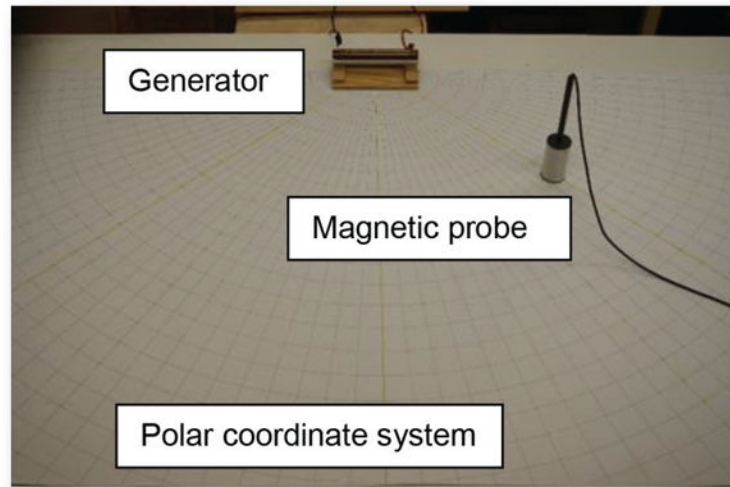
Figure 3.
Setup of the generator, magnetic probe and measurement coordinate system with no steel present.
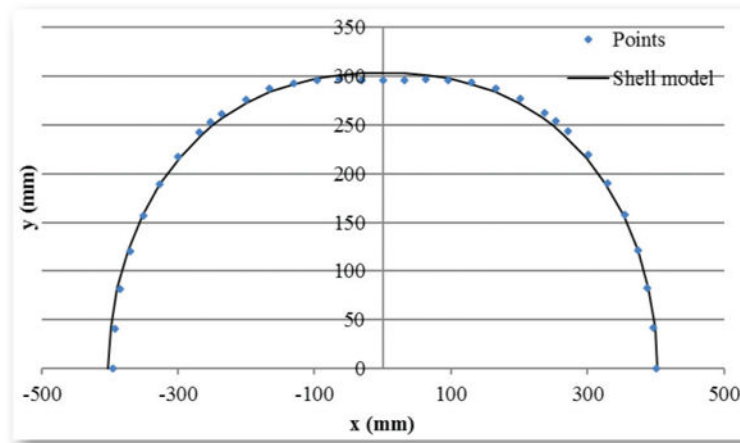
Figure 4.
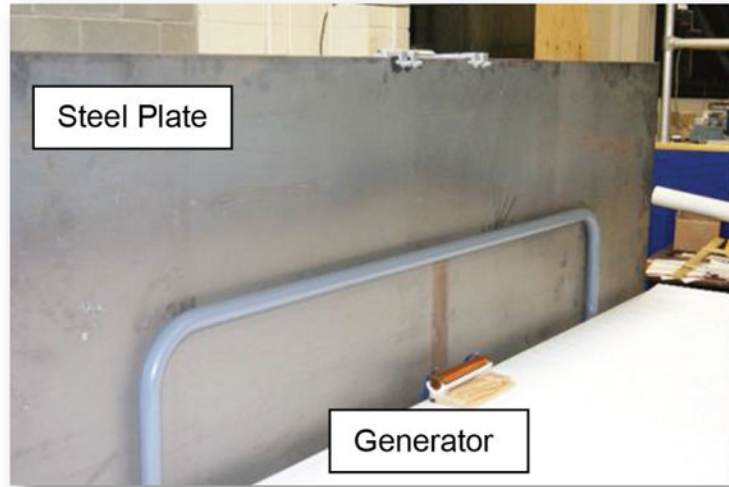Set of 33 measurements and the resulting shell with no steel present and $B = 110.9$ mG.

Figure 5.
Setup with the steel plate placed near the generator.
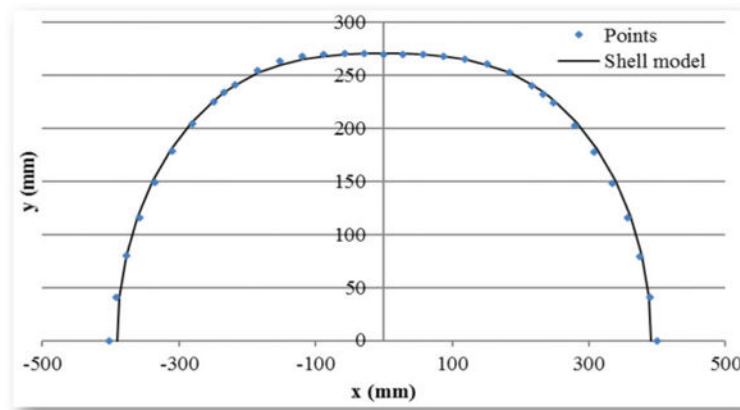
Figure 6.
Set of 33 measurements and the resulting half-shell with the steel plate present for $B = 176.9$ mG.
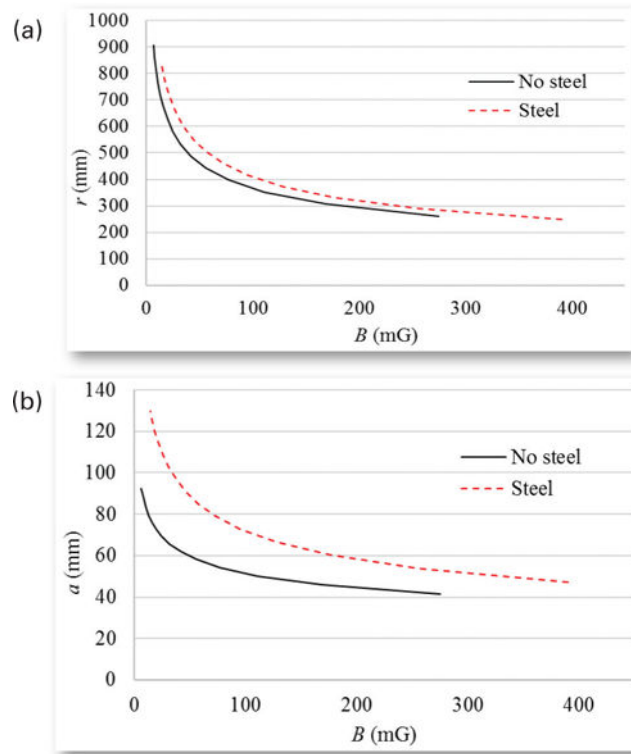
Figure 7.
Comparison of magnetic shell variable component (a) *r* and (b) *a* for the absence and presence of the steel plate with *B*.
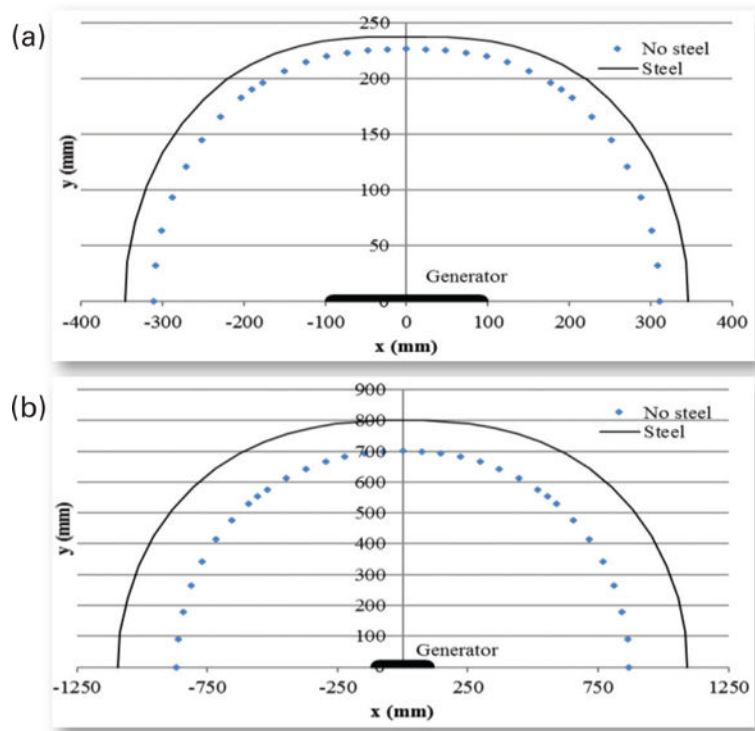
Figure 8.
Comparison of the half-shells obtained with and without the steel plate present (a) near the generator at $B = 250$ mG and (b) at a far distance from the generator at $B = 10$ mG.
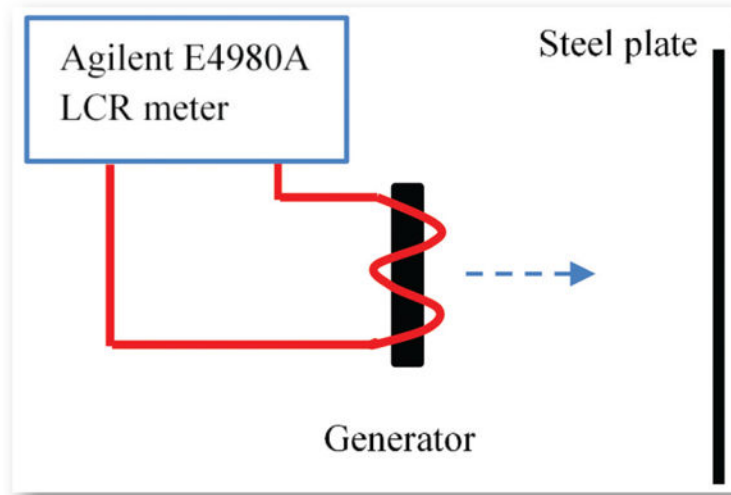
Figure 9.
Setup for measuring the influence of the steel plate on the electrical parameters of the generator.
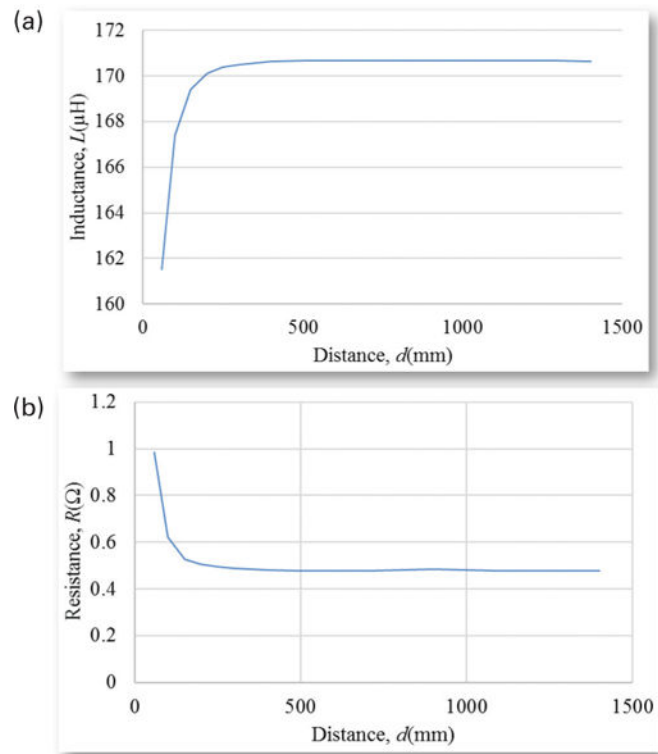
Figure 10.
Relationship between (a) inductance and (b) resistance of the generator circuit and distance to the steel plate.

Table 1

Comparison of the magnetic field distribution model constant parameters with and without the steel plate present.

	With no steel plate present	With steel plate present	Change (%)
c_r	1,690.4	2,201.0	30.2
d_r	0.333	0.366	9.91
c_a	138.2	204.87	48.2
d_a	0.215	0.307	42.8