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REVIEW

The Influence of a Continuous Mining Machine and Roof/Rib Mesh on Magnetic Proximity Detection Systems

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Abstract

Magnetic proximity detection systems (PDSs) are used with continuous mining machines (CMMs) to protect miners from striking and pinning accidents. Generators are used in a PDS to create magnetic fields covering the space around a CMM. The PDS determines the proximity of a miner relative to the CMM based on the magnetic flux density detected by a miner-wearable component (MWC) and simultaneously alerts the miner and stops the motion of the CMM if the miner is within a proximity that creates a striking hazard. A stable magnetic field is essential to the accuracy of the proximity calculations performed by the PDS. This paper presents the results of a systematic study of the magnetic influence of two types of steel structures found near a CMM—the body of the CMM itself and the wire mesh used for roof and rib control. The results show that the steel of the CMM body can change the magnetic field distribution and also alter electrical parameters of a PDS by changing its generator current. The study also shows that, depending on the distance between the wire mesh and a generator, the magnetic field can also be altered.

Keywords Magnetic distribution · Proximity detection system · Wire mesh

1 Introduction

Continuous mining machines (CMMs) can be approximately 11 m (37 ft) in length and more than 3 m (10 ft) in width. These machines perform the coal cutting operations in underground room-and-pillar coal mines. Between 2008 and 2017, continuous mining machines were involved in machinery accidents resulting in 237 lost-time injuries, 6 permanent disabilities, and 12 fatalities [2].

Because of these fatalities and injuries, the Mine Safety and Health Administration (MSHA) promulgated a regulation in 2015 that requires the use of proximity detection systems (PDSs) on all CMMs with the exception of full-face machines [12]. Currently, there are five different proximity detection systems that MSHA has approved as permissible for use in US underground coal mines. All of these PDSs require miner-wearable components (MWCs) to detect the magnetic fields that PDSs produce around a CMM [14]. These systems measure the magnetic field strength readings in terms of magnetic flux density from the MWC to determine whether a miner is at a safe distance from the CMM. Therefore, a stable magnetic field is essential for the accuracy of a PDS.

Research findings show that metallic objects within the system magnetic field can cause distortions of and changes to the field distribution [3, 8]. When a PDS is installed on a CMM, the systems are calibrated and compensated for the mass of the CMM itself. As long as no physical changes occur, the PDS provides a consistent response to the CMM operator, thus training the operator where safe and non-safe areas are relative to the CMM to avoid striking and pinning accidents. If physical changes occur, such as changes in generator position or location, additions of steel structures near the generators, or the presence of mine mesh for roof and rib control, the magnetic field distribution produced by the PDS will be altered. This can cause positional variance in the warning and stop zones around the CMM, which would change where the CMM operator can be safely positioned.

Because the presence of metallic objects may vary throughout the mining environment, the PDS zones could potentially vary from cut to cut or even progressively as the machine travels down an entry. This lack of consistency has the

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potential to reduce the trust of CMM operators, ultimately leading to incidents and accidents [13]. Lack of reliability in a decision-making aid (such as for air traffic controls) has been shown to reduce or eliminate its safety gains [11].

2 Method

This study systematically compared the magnetic field distributions obtained with and without the presence of a CMM and wire mesh. The magnetic field created by a generator covers a 3D spatial volume around the generator. This paper focused on the comparison of the field distributions on a horizontal plane and provided data for a basic understanding of the influence of the steel body of a CMM in the presence of mesh in the magnetic field.

Researchers from the National Institute for Occupational Safety and Health (NIOSH) previously established a shell function (in Eq. 1) that mathematically describes the magnetic field distribution pattern in air around a generator with no metal mass nearby [1, 4–6]. In Eq. 1, ρ denotes radial distance from the generator center to a point on the shell; $a\cos(2\alpha)$, the shape offset, describes shape variation from a circular shell of radius b; α is the angle of the ray from the generator center to the measurement point on the shell as shown in Fig. 1. A shell represents the magnetic field distribution pattern and is a collection of points measured with a given magnetic flux density, B. For each value of B, there is a unique shell. In an environment composed of a substance such as air, which has the same permeability throughout, the greater that B is, the smaller the shell will be and therefore the closer to the generator.

$$\rho = a\cos(2\alpha) + b \tag{1}$$

Because of the uniqueness of a shell for a given B under given conditions, the effect of a change in conditions on the magnetic field distribution can be quantitatively determined by comparing the shells for a given value of B. This study compared the shells with and without the presence of a CMM and wire mesh.

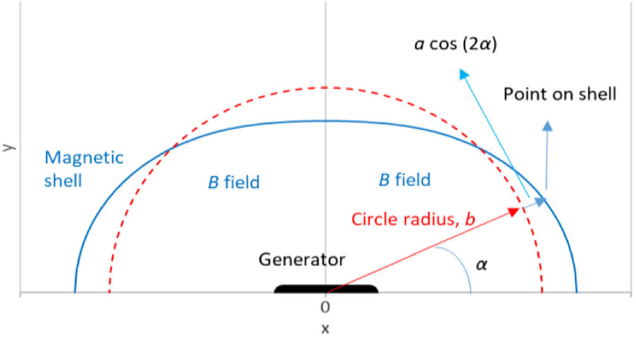

Fig. 1 A magnetic shell with its two components for the shell's radial distance ρ: $a\cos(2\alpha)$ and b

Previously, NIOSH researchers used this method to identify the influence of coal and rock on the magnetic field distribution of proximity detection systems; it was concluded that the influence was insignificant [7]. The method was also used to quantify the influence of a large steel plate on the magnetic field distribution of a proximity detection system; it was concluded that the plate had a significant influence on the magnetic field distribution [8].

Magnetic flux density B is directly proportional to generator current. To prevent fluctuation of B due to a current fluctuation caused by external environmental factors, the current to the generator is controlled to maintain it at the same value throughout this study.

3 Experimental Results

3.1 Instrumentation

Figure 2 shows the principal block diagram of the instrumentation used in this experiment. In the diagram, the signal generator provides a 73.6-kHz signal that feeds to the RF amplifier. The amplifier provides a current sufficient to drive the generator and produce the desired magnetic field. The current flowing through the generator is measured by the current probe, and monitored with a Fluke 125 multimeter.

Figure 3 shows the horizontal plane polar coordinate system and the generator position on the wooden platform used in this experiment. The figure also shows the tri-axial magnetic probe of the IDR-200. The meter provided a vector-sum magnetic flux density reading in milliGauss (mG) at any given point on the coordinate system.

The same instrumentation was used for all of the experiments in this study. Several hundreds of points were measured at different locations on the printed polar coordinate system placed on the wooden platform with a Gaussmeter to obtain a field distribution covering an area of 0.9 m × 2.4 m.

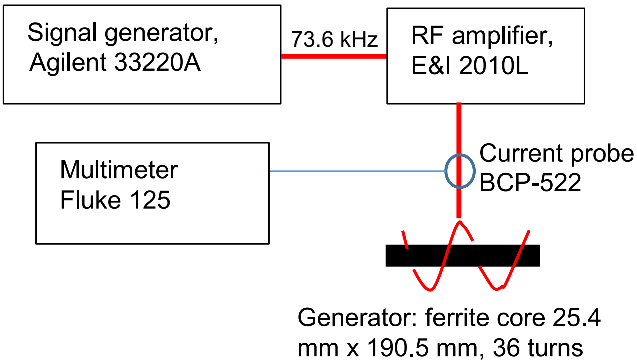

Fig. 2 Instrumentations used for magnetic field generation

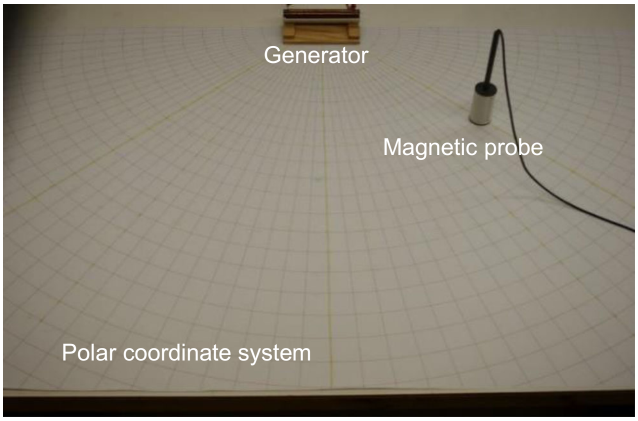

Fig. 3 The setup for the plane coordinate system, generator, and magnetic probe

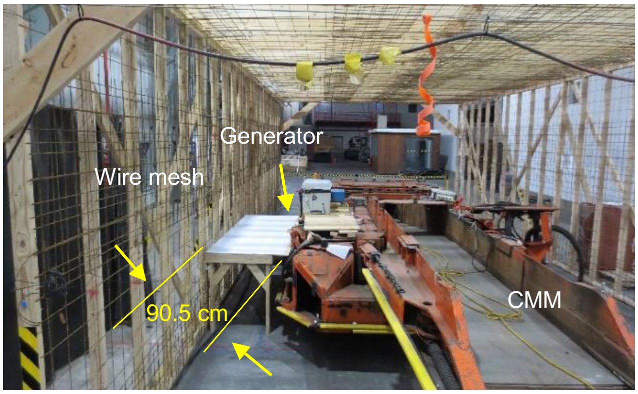

Fig. 5 The experimental system positioned between the CMM and the wire mesh rib

3.2 Experimental Setups

There were three setups in this study. In the first, the system was positioned with no metal body nearby. The second setup positioned the system close to a CMM with no wire mesh present (Fig. 4). The third setup positioned the system between the CMM and a wire mesh wall in a simulated coal mine entry (Fig. 5). The first setup produced a baseline field distribution with no external metallic influences. The second setup produced a field with the influence of a CMM only. The third setup produced a field with the influence of both the CMM and wire mesh.

In both the second and third setups, a 6-cm (2.4-in) gap was set between the generator and the body of the CMM. The wire mesh is a 15.24-cm (6-in) square pattern of 4-mm (0.162-in) steel wire. The dimensions of the simulated mesh entry are 12.2 m × 5.5 m × 3 m (40 ft × 18 ft × 10 ft). The mesh covers the roof and both ribs.

The influence of the CMM on the magnetic field in the absence of mesh is illustrated with two sets of half shells in Fig. 6, corresponding to magnetic flux densities of 340 mG and 6.5 mG both with and without the CMM present.

Figure 6 clearly shows an enlargement of the shells when the generator was close to the CMM, indicating an enhancement of the field by the CMM steel body. It also shows that the further the measurement is made from the generator (or the smaller the *B* value), the greater the enhancement appears. This is due to the fact that the magnetic field distribution is highly nonlinear with distance from the generator.

This is, however, not always the case when a wire mesh is introduced into the field. The influence of the mesh on the magnetic field is illustrated in Figs. 7 and 8.

Figure 7 shows two sets of magnetic field distribution shells near the CMM in the space between the CMM and the mesh. The set of three small shells was obtained with a measurement *B* of 275 mG and the set of three large shells with 21 mG. Measurements were taken within an area between the generator and two-thirds of the way to the mesh. Within this area, there was no discernible influence of the mesh as compared to the influence of the CMM alone. This suggests that any enhancement of the field due to the mesh is minor in this area.

Figure 8 illustrates the influence of the mesh on the field distribution when a measurement is closer to the mesh. The figure shows the difference between the actual field measurements of $B = 8.8$ mG, indicated by diamond markers, and the model prediction in a solid curve. The solid model shell was produced using the same magnetic flux density assuming the absence of mesh. The measurements in the presence of the

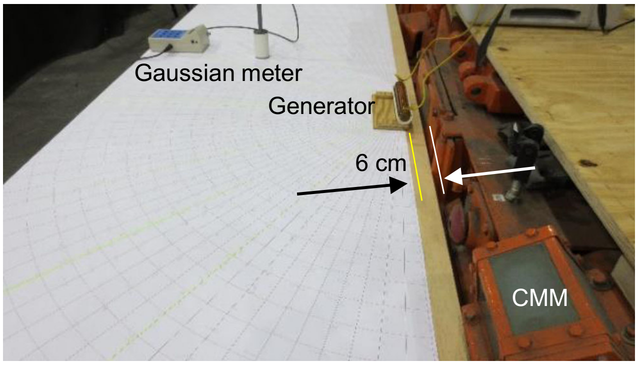

Fig. 4 The generator positioned near the CMM with no mesh nearby

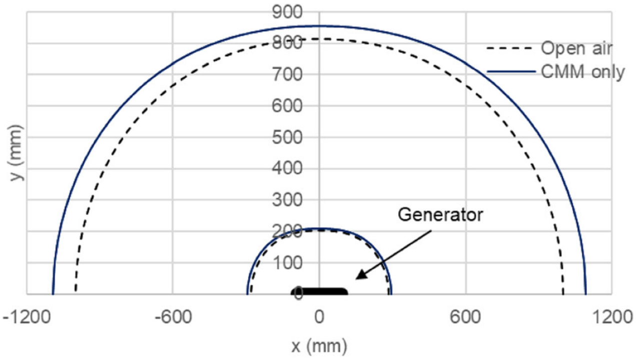

Fig. 6 Comparison of magnetic field shells with and without the presence of the CMM

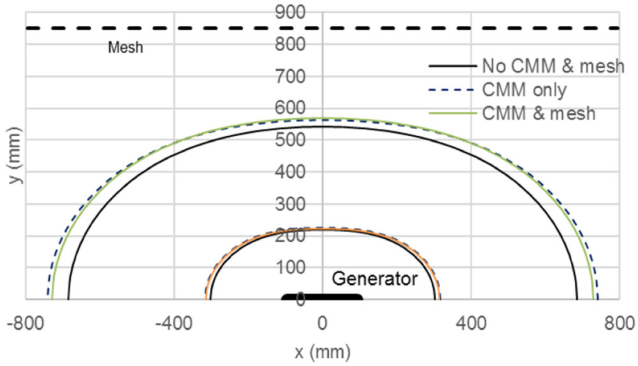

Fig. 7 Part of magnetic field distribution close to the CMM. The straight dashed line on the top represents the wire mesh. The position of the mesh wall as it relates to the generator is also illustrated

mesh clearly show a departure from the model when taken closer to the mesh. The measurements show that the magnetic flux density increases rather than decreases as the measurement approaches the mesh. This suggests that for this particular testing setup, the mesh gradually strengthens its influence within 20 cm (approximately 8 in.), and starts to significantly distort the field near it when it is closer than 15 cm (approximately 6 in.) to the wire mesh.

The steel of the CMM body and wire mesh can not only change the magnetic field nearby, but also alter the electrical parameters of the generator as shown in Table 1. This is due to the fact that steel is a type of electrical conductor which can serve as a load on the generator and modify the measured electrical parameters. A change of these parameters will lead to a change of generator impedance, resulting in a generator current change and field flux density change if not compensated for. Consequently, a location calculated from the magnetic density measurement can be affected.

4 Discussions

The current study investigated the effects of the steel body of the CMM and wire mesh on the magnetic field distribution of a PDS. Results indicate that both the CMM and wire mesh can alter the magnetic fields. In this section, the authors outline key study findings, potential mitigation strategies, and future considerations.

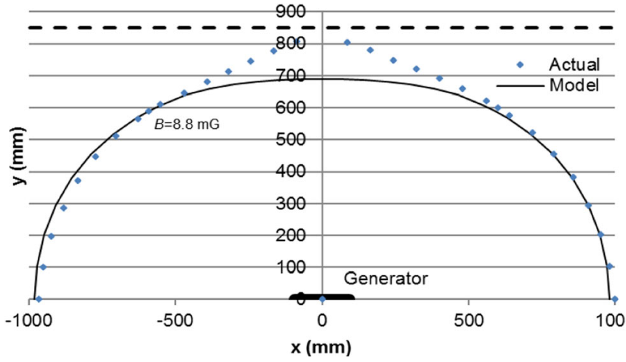

Fig. 8 Comparison of the measured and modeled magnetic fields between the CMM and the mesh

As shown in Table 1, the steel body of both the CMM and mesh can alter the electrical parameters of the generator, which can cause the corresponding generator current to change, resulting in a change in the magnetic field and possibly affecting system accuracy. To maintain good system performance, it is essential to have a steady current to the generator. An automatic control system can be used by a PDS to help stabilize the generator current. NIOSH researchers have shown that a feedback control system can be used to stabilize the generator current, which is also affected by changes in temperature [9]. However, a generator current feedback control system would not entirely correct the influence of mesh. An MWC that can provide an accurate and non-distorted measurement of the magnetic field is also essential in addition to a stable magnetic field from the generator. With a PDS's magnetic field stabilized, along with an accurate MWC, other mitigation measures can then be considered to further improve the PDS performance.

As shown in Section 3, the net effect of the steel body of a CMM is the enhancement of the magnetic field with no notable change to the magnetic distribution pattern. This suggests that the accuracy of a PDS can be maintained as long as a PDS is re-calibrated after it is installed on a CMM or relocated on the CMM. The enhancement of the magnetic field by the steel body of the CMM is, thus, accounted for. The accuracy of the generator current can then be maintained by an automatic control system.

As presented in Fig. 8, the steel wire mesh shows a strong alternation of the magnetic field of a PDS only at close range. Keeping MWCs further from the mesh would minimize the influence of the mesh on the accuracy of the PDS. For a PDS without an automatic control system to stabilize its generator current, operating in an entry entirely covered with steel wire mesh on its ribs, this can be an administrative solution to mitigate the influence of the mesh on the PDS. Although this is a non-cost and effective mitigation strategy, this is not a systematical solution. Furthermore, given the confined space and visibility limitations of the underground environment, there may be some situations where separation is not possible.

A possible systematical solution to mitigate the influence of the wire mesh could be to substitute it with a non-metal mesh, as long as this substitution does not adversely affect safety in terms of ground control. A laboratory test of a large piece of plastic mesh shows that it has no influence on the magnetic field of a PDS. Such a substitution does not necessarily need to cover the entire entry, but only the lower part of an entry where an MWC or CMM can come close to it.

Another advantage of using non-metal mesh is that the mesh will no longer cause a change in generator current and the corresponding magnetic field. Our supporting

Table 1 Measured generator electrical parameters at f = 73.6 kHz (L inductance, R resistance, Q quality factor)

Generator electrical parameters	No metal mass nearby	6 cm from CMM	Between CMM and mesh
L (μH)	174.18	165.21	164.06
R (Ω)	0.4449	1.256	1.094
Q	181.06	60.62	69.32

experimental results have shown that the generator current can change at a close distance between the generator and the steel wire mesh.

In addition, variations in the magnetic fields could influence the behaviors of mineworkers. Because the magnetic fields expand in the presence of a CMM or steel wire mesh, variations could result in false alarms or unwarranted warnings. Past studies have shown that false alarms can have an adverse effect on users' trust in and use of automated systems [10, 13]. In some cases, false alarms have caused workers to stop using or relying on a system [10, 13]. Relative to PDSs, this type of behavior could have a negative impact on mineworkers' safety. To help prevent unsafe responses, mine operators and leaders could discuss specific conditions that alter the PDS's magnetic fields as a part of their training.

5 Limitations

This study was limited to one experimental laboratory environment, and the measurements were conducted within a small area. Additional work would be required in order to acquire more measurements for an analysis of the influence of the CMM and mesh in an extended entry or a different environment. The method and measurement results presented in this paper can serve as a reference for such future work.

6 Conclusions

The current study investigated the influence of the steel body of a CMM and wire mesh on the magnetic field of a proximity detection system. The mesh was installed on the roof and both ribs of a simulated coal mine entry. The study's measurements show that the steel body of the CMM can enhance the magnetic field in the open space in front of the PDS generator. The mesh can also enhance the field in the space close to it. The enhancement increases as a measurement gets closer to the mesh and further from the generator. The measurements also show that the steel body of the CMM and the mesh can alter the electrical parameters of the generator. Understanding their influence on a PDS can lead to improved design and accuracy by minimizing adverse influences. With this better understanding of the influence of a CMM and wire mesh on a PDS, some mitigation solutions have been proposed in this paper. The solutions include using an automatic control system to help stabilize the generator current, conducting an on-site system calibration to account the influence of the steel body of a CMM on magnetic field distribution, and substituting steel wire mesh with non-metal one. An accurate PDS can make a CMM safer to operate, which in turn will increase workers' safety.

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Disclaimer The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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