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INFLUENCE OF CABLE SPLICES ON THE MAGNETIC COUPLING FROM PROXIMITY DETECTION SYSTEMS TO TRAILING CABLES

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ABSTRACT

Proximity detection systems (PDSs) are a critical safety system used in the mining industry for protecting miners from pinning, crushing, and striking hazards. The magnetic fields from a PDS generator can be parasitically coupled to a trailing cable, which often causes false alarms and thus should be avoided. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have conducted extensive studies to investigate the major controlling factors of magnetic field coupling from a PDS generator to an un-spliced (i.e., continuous) trailing cable. Trailing cables, however, might have splices and whether a splice would affect (enhance or degrade) the parasitical coupling is still unknown. In this study, we designed an experiment to characterize the influence of a cable splice on the parasitic coupling. A commercial PDS with four magnetic field generators installed on a continuous mining machine (CMM) were used to generate the magnetic fields that are coupled to a trailing cable powering the CMM. Two splices were made with one close to one of the PDS generators (<1m) and the other one far (>5m) from all four generators. The coupled magnetic fields along the trailing cable were recorded before and after each splice was made. The results show that both splices introduce no significant changes to the coupled fields. The conclusions and findings in this paper can help better understand the safety concerns caused by parasitically coupling from PDSs to trailing cables.

INTRODUCTION

To protect mine workers from striking, pinning, and crushing injuries when they work around heavy machines such as continuous mining machines (CMMs), the Mine Safety and Health Administration (MSHA) published a final rule in 2015 which requires operators of underground coal mines to equip place-changing CMMs with proximity detection systems (PDSs) (MSHA 2015). Currently, all MSHA-approved PDSs are magnetic-field-based systems that operate based on a field-to-distance relationship calibrated prior to the use of PDSs. In other words, magnetic PDSs determine the position of a mine worker based on the magnetic field strengths received by the miner-wearable component (MWC) worn by the miner—the stronger the field strength, the closer the mine worker is located to the machine where the PDS generators are mounted.

In practice, there are some environmental factors that can alter the validity of the calibration and thus cause a PDS to be inconsistent in its performance. One example of such environmental factors is the presence of trailing cables. It is known that signals in the Medium Frequency (MF) band (300 KHz - 3 MHz) can be well coupled to existing underground conductors such as conduits, rail tracks, and power lines and then propagate for a long distance with a minimal power loss (Li et al. 2016). These phenomena are known as parasitical coupling and have been used in the underground by modern MF communication systems to combat the high signal power loss without a need to deploy new dedicated communication lines, which are often costly. The parasitical coupling, however, can significantly increase the magnetic fields received by an MWC and generate false alarms, which is a safety concern that should be avoided. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have conducted extensive studies to characterize the parasitical coupling from a PDS to a trailing cable (Zhou et al. 2019). Major factors for controlling the parasitical coupling were identified and mitigation strategies were proposed.

All prior studies pertaining to parasitical coupling, however, focused on the coupling from a field source to a continuous cable without any splices. In practice, trailing cables may have splices and whether a splice would affect (either enhance or degrade) the parasitical coupling is unknown.

Theoretically, a splice in a cable adds a discontinuity to the cable where energy might potentially be injected into or leaked from the cable, depending on the distance between the location of the splice and the field source (i.e., a PDS field generator). In this study, we designed an experiment to investigate the influence of cable splices on the magnetic fields coupled from a PDS generator to a trailing cable.

Measuring the Coupled Magnetic Fields from a PDS to a Trailing Cable

Figure 1 shows the experimental setup for measuring the coupled magnetic fields based on an MSHA-approved PDS. The PDS has four generators (labeled from Gen 1 to Gen 4) which are mounted on the two sides of a CMM. Each generator transmits a short duration of magnetic field signal at a frequency of 73 KHz in a known sequential order. An MWC is used to measure the three-axis magnetic field (i.e., Bx, By, and Bz). The magnetic fields measured by the MWC are wirelessly (at 915 MHz) transmitted back to a controller box installed on the CMM. A laptop is then used to wirelessly (at 2.4 GHz) read the measured magnetic fields from the controller box through a LabVIEW program. The trailing cable (SHD-GC P-184-MSHA) which delivers the power to CMM and PDS is a standard shielded, heavy-duty cable that consists of five conductors. A photo of the experimental setup is shown in Figure 2.

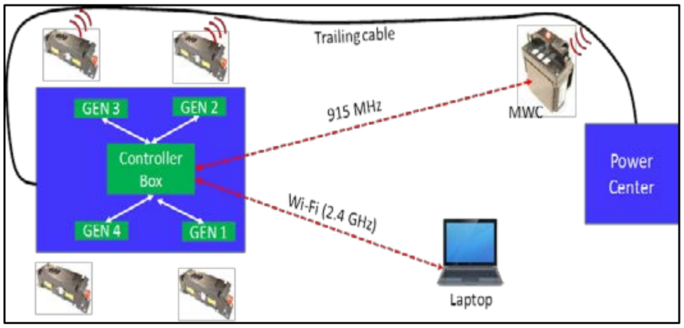

Figure 1. Experimental setup for measuring the coupled magnetic fields from a PDS to a trailing cable.

It should be noted that the measured magnetic field, collected using a laptop through a LabVIEW program, is a digital number from an analog-to-digital converter (ADC) without any specific unit (e.g., Gauss). These digital numbers, however, can be converted to true magnetic field values through proper calibrations. In this study, such a calibration has not been done as it is not needed since only relative changes of the field are of interest.

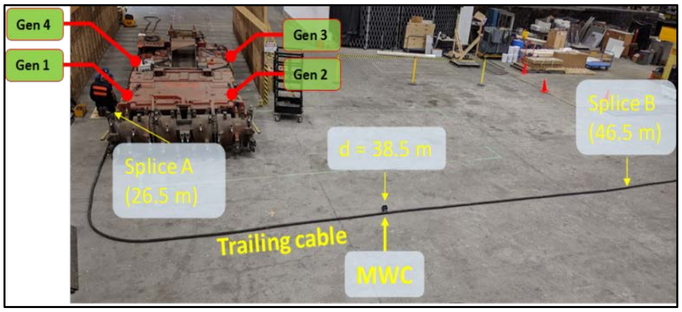

Figure 2. A photo showing the experimental setup for characterizing the influence of cable splices on parasitic coupling.

In addition, the coupled magnetic field received by an MWC generally mixes with the field that is transmitted directly from the field source (i.e., direct fields), and it is challenging to separate them. The approach we took to isolate the coupled field from the direct field was to create a scenario where the direct field is negligible as compared to the coupled field. As a result, the measured field would be dominated by the coupled field. Prior NIOSH studies have shown that distance is a major parameter for controlling both the direct fields (Zhou et al. 2018) and the coupled fields (Zhou, et al. 2019). Such a scenario can be established when the distance between the MWC and the field generator is far, while the distance between the MWC and the trailing cable is minimized. As a result, during the recording of magnetic fields, the MWC was always placed directly against the trailing cable and kept far from the field generator, as shown in Figure 2.

Prior NIOSH research has shown that the impedance of the coupling network plays a significant role in the effectiveness of the coupling (Zhou et al. 2019). As shown in Figure 3, in order to enhance the coupled magnetic fields, we connected the frame of CMM to a metallic pipe on one of the walls of the building to lower the impedance of the coupling network.

Figure 3. The metal frame of the CMM is connected to a metallic pipe on the wall of the building to enhance the parasitic coupling.

As shown in Figure 4, two permanent splices were made to investigate the influence of splices on the magnetic coupling, using an MSHA-approved splice kit (MSHA approval number: 7K-279146-MSHA). The first splice (labeled as Splice A in Figure 2) was made close to Gen 1 (<1 m) of the PDS and is 26.5 m from the beginning of the trailing cable with the zero-distance starting from the CMM end of the cable. Splice A was made to investigate whether a splice close to a field source would allow more energy to inject into the cable. The second splice (labeled as Splice B in Figure 2) was made far from all generators and is about 46.5 m from the beginning of the trailing cable. Splice B was made to investigate whether a splice would cause more energy to leak from the cable.

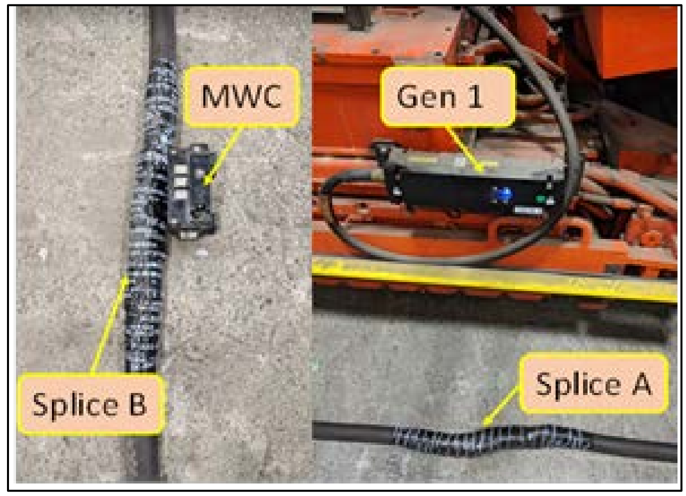

Figure 4. Two splices were made to investigate the influence of cable splices on parasitic coupling.

The trailing cable was marked every two meters. An MWC was moved along the cable and stopped on those markers where the magnetic fields received by the MWC were recorded using the system illustrated in Figure 1. The MWC remained stationary while 100 samples of the magnetic field reading from each of the four generators were recorded. Since each magnetic field reading includes three components (i.e., X, Y, and Z), there is a total of 1,200 readings recorded for every stopping point (distance marker) on the cable.

A preliminary quick test shows that the direct fields from all four generators become too weak to be measured by the MWC and thus are negligible compared to the coupled fields when the MWC is placed at 38.5 m or further. As a result, we started to record the magnetic fields at the distance of 38.5 m.

The field measurement at every two meters along the length of the cable (from 38.5 m to 76.5 m) was repeated four times. For the first time, the fields were measured with the cable being continuous (i.e., no splice). For the second time, the fields were measured after splice A was made. For the third and fourth times, the fields were measured after both splices A and B were made. There is no change introduced between the third and fourth field measurements, and the purpose for making the same measurement twice under the same condition was to check the repeatability of the measurement.

Two metrics, mean relative absolute difference ($\boldsymbol{\sigma_{mean}}$) and maximum relative absolute difference ($\boldsymbol{\sigma_{max}}$), are introduced to characterize the difference between the two field measurements:

$$\boldsymbol{\sigma_{mean}} = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{abs}\left(\frac{B_{2,d_i} - B_{1,d_i}}{B_{2,d_i}}\right) \quad \textbf{(1)}$$

$$\boldsymbol{\sigma_{max}} = \boldsymbol{max}\left(\boldsymbol{abs}\left(\frac{B_{2,d_i} - B_{1,d_i}}{B_{2,d_i}}\right)\right) \quad \textbf{(2)}$$

where $\boldsymbol{B_{1,d_i}}$ and $\boldsymbol{B_{2,d_i}}$ are the two measurements of the magnetic field at distance $\boldsymbol{d_i}$.

RESULTS AND DISCUSSION

Coupled magnetic fields: Figure 5 shows the measured magnetic fields at different distance markers along the trailing cable, before any splice was made. Unless stated otherwise, the fields presented in this paper are the vector sum of the three-axis fields measured by the MWC. They are also averaged fields over 100 samples collected. Only fields for Gen 4 and Gen 1 are presented in Figure 5 as the fields coupled from other generators (i.e., Gen 2 and Gen 3) are too weak to be reliably measured by the MWC. This can be explained by the fact that the cable was placed in such a way that it is close to Gen 4 and Gen 1 and far from Gen 2 and Gen 3, as illustrated in Figure 2.

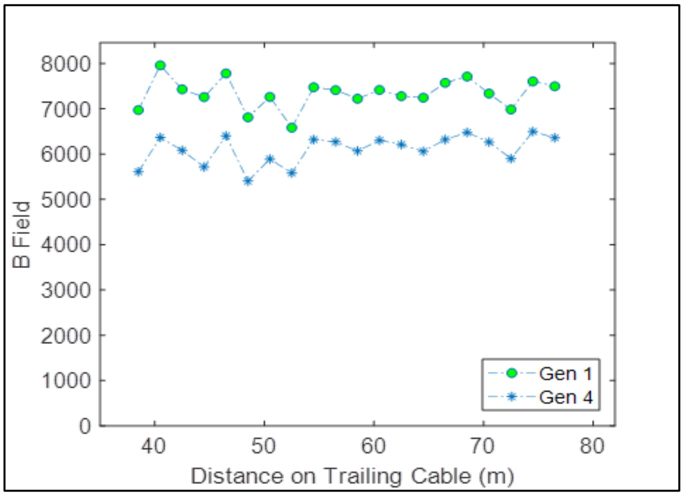

Figure 5. Measured magnetic fields coupled from different PDS generators (Gen 1 and Gen 4) to the trailing cable at different distances along the cable.

Another interesting observation from Figure 5 is that the measured fields from both Gen 4 and Gen 1 only show a very small attenuation rate along the cable. This is expected and is the reason why in practice PDS signals, after being coupled to a trailing cable, can be still detected far away from the machine where generators are mounted.

Repeatability test: Figure 6 shows a comparison of the magnetic fields (coupled from Gen 4) measured at two different times (separated by about half an hour). The comparison shows that there is only a minor difference $\boldsymbol{\sigma_{mean}} = \mathbf{1.5}\%$ and $\boldsymbol{\sigma_{max}} = \mathbf{4.9}\%$ when fields are recorded at two different times (denoted as "original result" and "repeated result" in Figure 6), indicating a good measurement repeatability. The coupled field without the extra grounding wire (as shown in Figure 3) is also plotted in Figure 6 to illustrate how the impedance between CMM and the ground affects the parasitic coupling. Unless otherwise stated, all results reported in this paper are collected with the grounding wire.

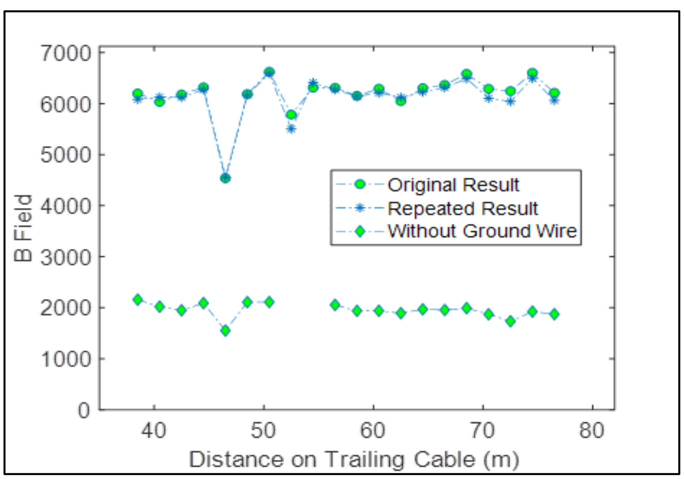

Figure 6. A comparison of the coupled magnetic fields (from Gen 4) measured at different times to show the repeatability of the field measurement.

The repeatability for measuring the coupled fields from Gen 1 is similar to that from Gen 4 which is shown in Figure 6. The calculated difference for measuring fields coupled from Gen 1 to the cable are:

$$\boldsymbol{\sigma_{mean}} = \mathbf{1.3}\% \text{ and } \boldsymbol{\sigma_{max}} = \mathbf{4.1}\%$$

Influence of splices on coupling: Figure 7 shows a comparison of the coupled magnetic fields (from Gen 1) along the cable with and without splice A. The calculated difference between the two measurements are: $\boldsymbol{\sigma_{mean}} = \mathbf{3}\%$ and $\boldsymbol{\sigma_{max}} = \mathbf{8.3}\%$. Although the field variation caused by splice A is greater than the field variation shown in the repeatability test where no change was introduced, overall, these field variations are small and often can be ignored. In addition, the small field variation presented in Figure 7 could be caused by the fact that the trailing cable was not perfectly restored to the original position after splice A was made, rather than by the presence of splice A. It is known that the coupled field is very sensitive to the distance between the cable and the generator when they are located close to each other, and a slight change in the position of the cable could lead to a significant change on the coupled field.

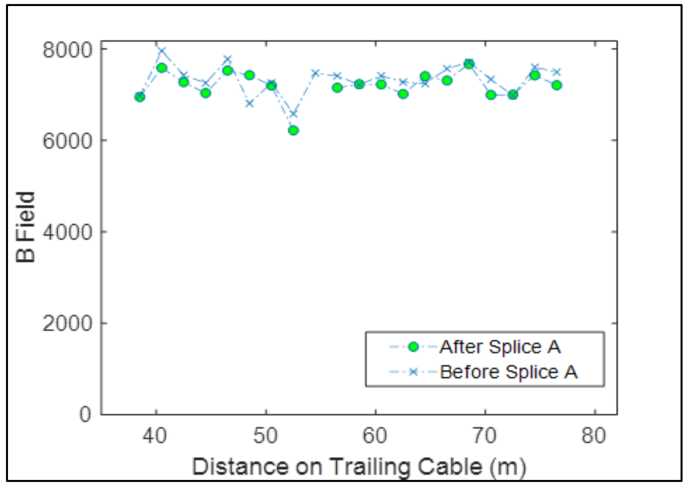

Figure 7. A comparison of the coupled magnetic fields (from Gen 1) along the trailing cable with and without splice A.

Figure 8 shows a comparison of the coupled magnetic fields (from Gen 1) along the cable with and without splices A and B. Similarly, it is shown that the fields measured before and after two splices match each other well (with $\boldsymbol{\sigma_{mean}} = \mathbf{4.5}\%$), indicating that no significant change is caused by the two splices on the cable. In Figure 8, the field at d=46.5 m after splice B was made is found to be noticeably lower than the field measured before the splice was made. This lower field reading is likely due to the fact that the cable became thicker (caused by tapes used to wrap up the cable, as shown in Figure 4) after the splice, considering that splice B was made exactly at that location (i.e., d=46.5 m). As a result of thicker cable, the MWC, when placed against the cable, was actually farther away from the conductor part of the cable which causes MWC to measure a weaker magnetic field.

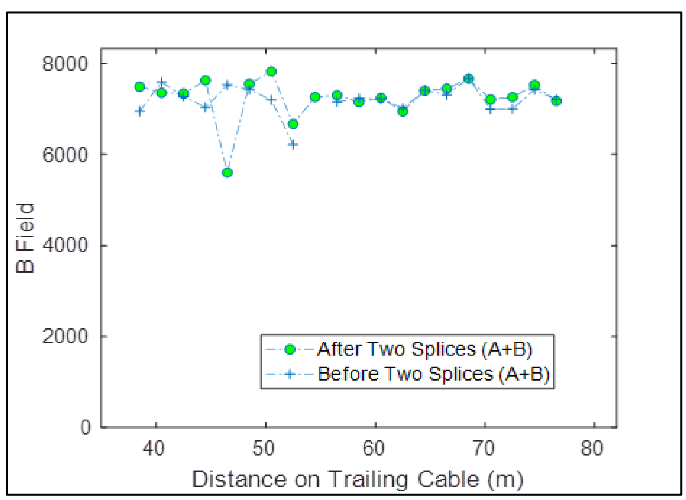

Figure 8. A comparison of the coupled magnetic fields (from Gen 1) along the trailing cable before and after the two splices (splice A and splice B) were made.

CONCLUSIONS

In this paper, we demonstrated that magnetic fields from a commercial PDS installed on a CMM can be parasitically coupled to a trailing cable powering the CMM. It is shown that this parasitic coupling is enhanced when the distance between the PDS and the cable (referring to either the distance between a generator and the cable, or the distance between the MWC and the cable) is decreased. Experiments were designed to investigate whether a splice on the trailing cable would affect this parasitic coupling. Two splices were made with one close to a PDS generator and the other far from the generator. The experimental results show that both splices introduce no significant change to the coupled magnetic fields. As a result, the splices on a cable can be ignored when one evaluates its parasitic coupling performance. The conclusions and findings in this paper can help better understand the safety concerns caused by parasitically coupling from a PDS to trailing cables in underground coal mines.

The measurements reported in this paper were done on the surface with the CMM pump motor not running. As a result, the experiment did not account for the effects caused by the large time-varying currents in the trailing cable when the CMM is cutting or moving. Additional testing should be conducted in an underground environment with the presence of significant currents in the trailing cable.

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DISCLAIMER

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

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