# FEA Of A Differential Eddy Current Sensor For Railway Infrastructure Condition Monitoring

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## Abstract

Increased traffic and load on railway infrastructure require regular inspection of track components. Railway track elements such as fasteners, insulation joints, and weld joints are subjected to extreme loading conditions, making their regular inspection essential for ensuring the safety and punctuality of railway operations. Existing manual inspection methods are time-consuming, labour intense, unsafe, and expensive. Railway infrastructure maintenance companies in Europe are seeking alternative automated solutions enabled by data-driven models and sensors installed on in-service trains. Lindometer, a differential eddy current sensor developed by Alstom Sweden, is designed to be mounted on in-service trains[1]. The non-contact, highly sensitive nature of the sensor system makes it resilient to high train speeds and robust against environmental challenges.

One of the primary challenges in developing effective data-driven anomaly detection models is the imbalanced nature of real-world datasets. In the context of this study, which focuses on detecting abnormal track conditions, the dataset is heavily skewed toward normal operational states, with anomalous instances being extremely rare. To address this imbalance, synthetic data representing abnormal track conditions generated using finite element methods (FEM), enables the model to learn from a broader spectrum of operational scenarios.

Fig. 1 shows an electromagnetic FEA model of the interaction between an eddy current sensor and a rail, developed using the AC/DC module in COMSOL. The rail includes a small 1 mm gap, representing a simplified model of insulation joints typically found in railway tracks. The sensor is positioned 10.5 cm above the rail surface. The sensor setup consists of a source coil and two differentially coupled pickup coils. The source coil is excited using the edge current feature, while the pickup coils are modelled as 2D rectangles. The induced voltage in the pickup coils is calculated virtually using Faraday's Law of Induction, meaning the EMF is proportional to the time rate of change of the magnetic field[2,3]. The analysis is carried out in the quasi-static frequency domain, and the movement of the sensor setup along the rail is simulated using a parametric sweep.

Fig. 2 illustrates the magnetic flux density distribution over the rail specimen. As shown in Fig. 2(a), the magnetic flux density is concentrated under the sensor setup and appears uniformly distributed, indicating the presence of induced eddy currents on the rail surface. However, as the sensor passes over the gap, the magnetic flux distribution is disturbed, as seen in Fig. 2(b). The induced voltage in the pickup coils is plotted against the sensor displacement in Fig. 3 (a). A noticeable spike in the induced voltage occurs as the sensor approaches the air gap, followed by a drop as the sensor moves past it. Fig.3 (b) presents an IQ plot of the induced voltage, separating the signal into in-phase (I) and quadrature (Q) components. This decomposition provides a more detailed analysis, making it easier to detect subtle changes in the rail's material properties, especially in the presence of defects. Fig.4 shows the animation of sensor movement over the rail surface and corresponding magnetic flux density.

In conclusion, a FEA model of the eddy current sensor - rail insulation joint's interaction is developed in COMSOL AC/DC module and is solved in the frequency domain. The model reacts to the disturbances on the railway track leading to identification of gaps or Insulation joints. In future, a sophisticated model of Insulation joints would be developed to capture a realistic behaviour of the sensor-specimen interaction and to develop synthetic data to train data driven model for anomaly detection.

## Reference

[1] P. Chandran et.al, “Train based differential eddy current sensor system for rail fastener detection,” Measurement Science and Technology, vol. 30, 09 2019.

[2] R. P. Feynman, Feynman Lectures on Physics: Electrical and Magnetic Behavior. Volume 4. Perseus Books, 1999.

[3] O. Bíró, “Edge element formulations of eddy current problems,” Computer Methods in Applied Mechanics and Engineering, vol. 169, no. 3, pp. 391–405, 1999.

## Figures used in the abstract

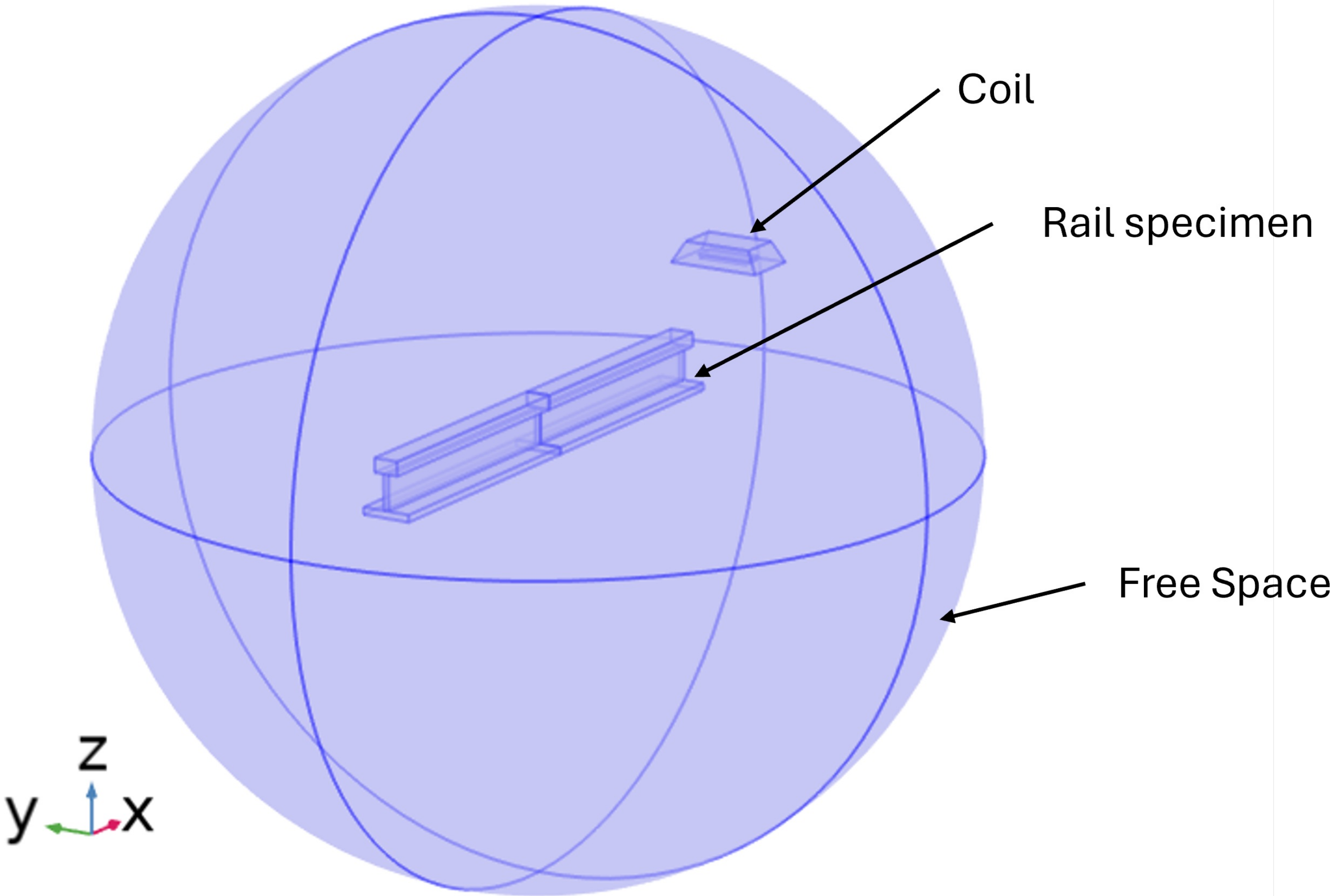



**Figure 1** : Sensor-Rail interaction model setup in COMSOL

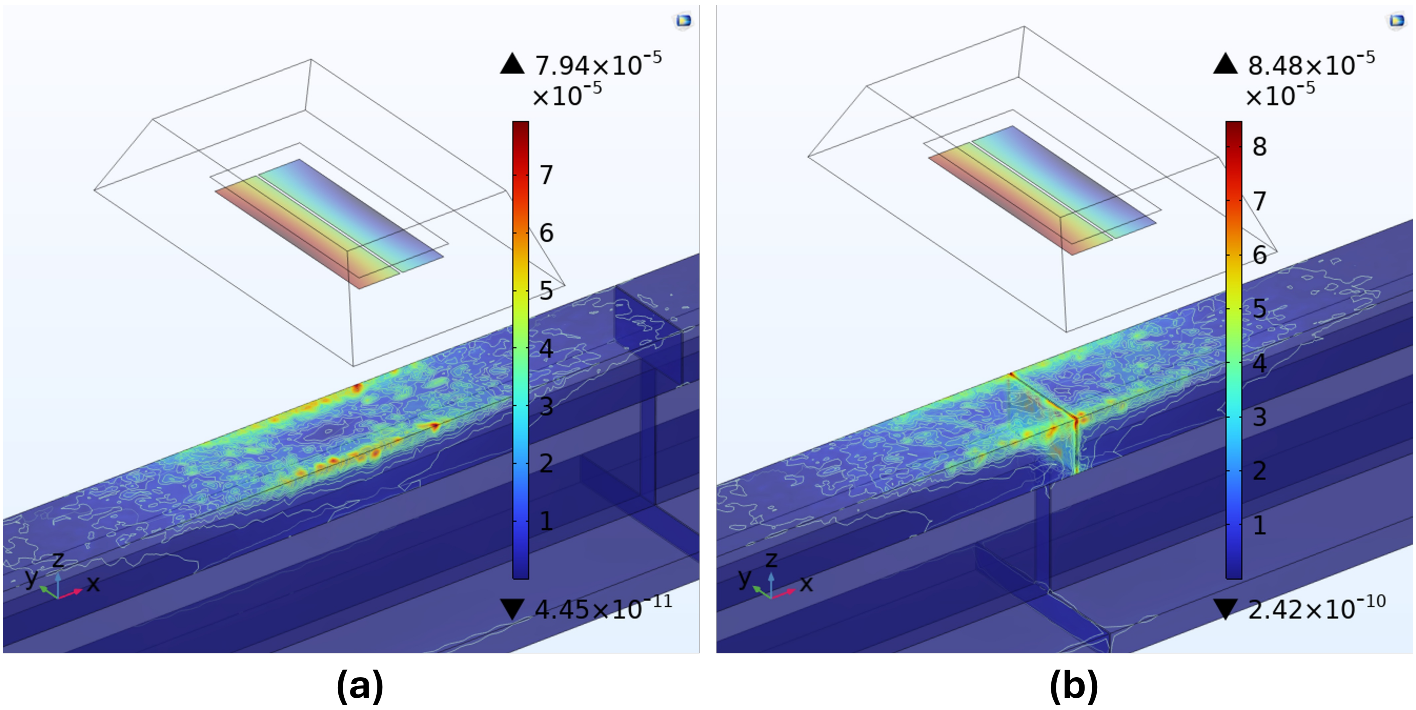
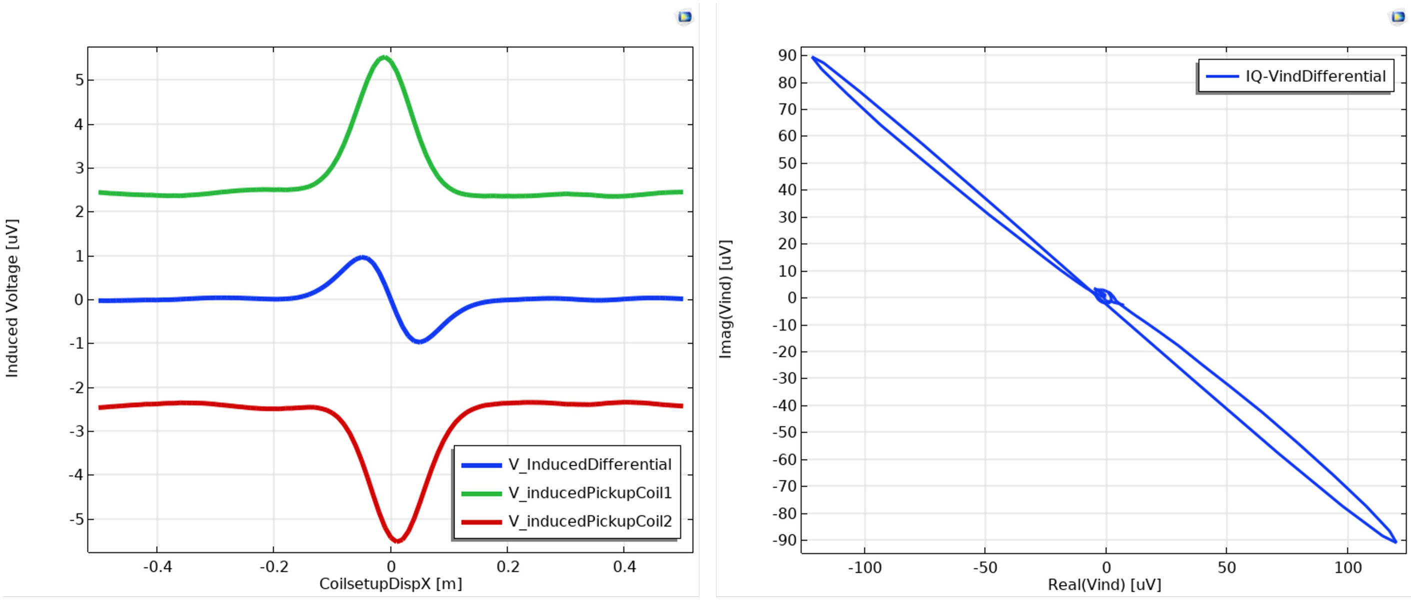



**Figure 2** : Magnetic flux density distribution on intact-rail vs rail with a gap




**(a)** **(b)**

**Figure 3** : Induced voltage vs sensor movement and IQ plot

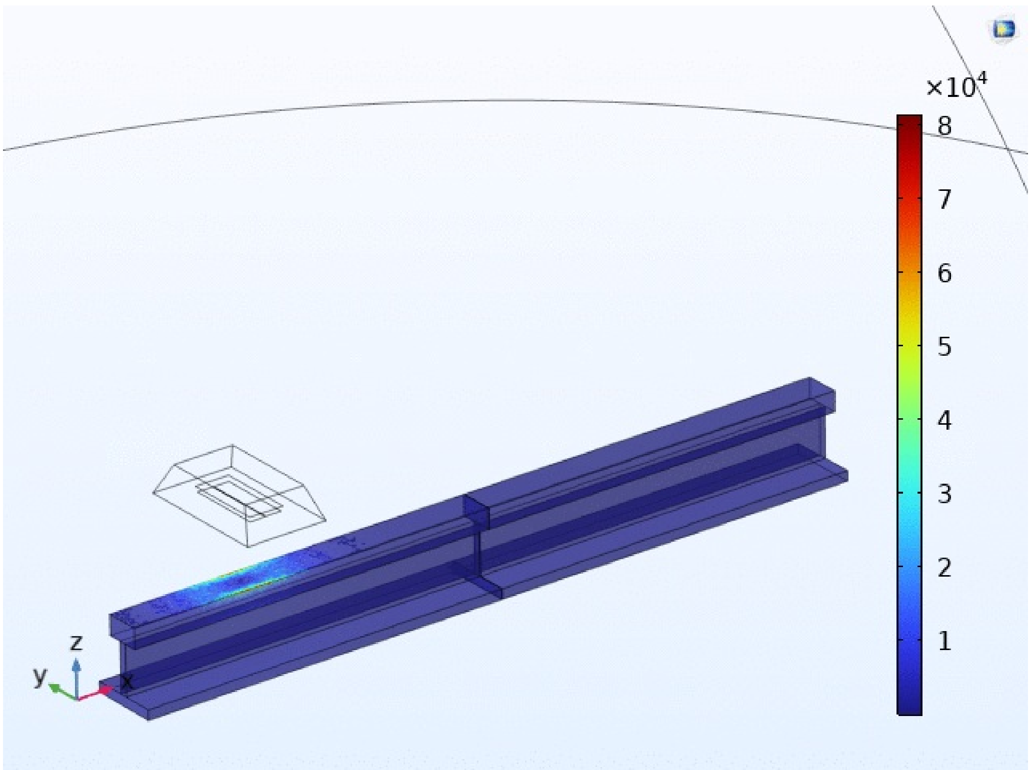



**Figure 4** : Visualization of sensor movement and corresponding magnetic flux density movement