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A Static Coil Misalignment Study Using Gaussian Curve Fitting: Foundations for Sensorless Dynamic WPT

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Lateral misalignment poses a significant challenge in the field of wireless power transfer, particularly in dynamic systems where the receiver coil exhibits relative motion to the transmitter. Although many earlier studies have primarily focused on advanced coil designs in dynamic scenarios, this research investigates how circular coils that are integrated with sensorless-based algorithms behave when subjected to static lateral shifts within a distance of −10 cm to +10 cm. Root-mean-square current readings were collected systematically, and the Gaussian curve fitting method was applied to accurately depict the spatial changes of the circular coil magnetic coupling. The assessments were also carried out with vertical coil distances set at 2.5 cm, 3.5 cm, 4.5 cm, and 5.5 cm. The measured data suggest that peak Irms values experience a steady decline as the air gap is increased, accompanied by a concurrent increase in Gaussian spread, highlighting a coupling region that is more sensitive to changes in system parameters. The centre alignment metric hovered around zero, indicating that the coils were aligned correctly and the reliability of the positioning setup. The implementation of the inverse Gaussian model facilitated the estimation of lateral displacement in the absence of positional sensors, with measurement errors typically kept within ±1.5 cm. Additionally, the peak-to-peak voltage exhibited an exponential decay characteristic as the vertical distance increased, consistent with the expected decline in magnetic coupling effectiveness. Although the experimental arrangement was performed under static (non-moving) conditions, the results establish a predictive modelling framework that serves as a hypothesis for real-time estimation in future dynamic wireless power transfer applications.

Keywords: Dynamic Wireless Power Transfer (DWPT); Lateral Misalignment Modelling; Circular Coil Geometry; Mutual Inductance Estimation; Gaussian Curve Fitting

I. INTRODUCTION

Dynamic Wireless Power Transfer (DWPT) is recognised as a more advanced method of allowing electric vehicles (EVs) to charge while in transit. Among the primary obstacles encountered in implementing DWPT systems is maintaining high power transfer efficiency (PTE) when subjected to coil misalignment, particularly in lateral displacement and vertical offset between the transmitter (Tx) and receiver (Rx) coils. Lateral displacement, which represents the horizontal difference between the centres of the coils as the vehicle moves, can significantly decrease mutual inductance and increase leakage flux, resulting in a decrease in efficiency. Given that vehicles are constantly engaged in lane changes, steering corrections, and different road conditions, eliminating coil misalignments during transit can be significantly challenging. Over the years, numerous research studies have been conducted to mitigate this issue, including the development of advanced coil structures, compensation arrangements, and control approaches. Although a variety of

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*Corresponding author's e-mail: jabbar@uthm.edu.my strategies have produced significant improvements, the solution often relies on complex technology or supplementary sensors, which consequently increases overall system costs and hinders scalability. This has led to a growing interest in sensorless methodologies that can rectify misalignment in real time, relying solely on the intrinsic electrical responses of the system. To illustrate the fundamental configuration of a DWPT system, Fig. 1 depicts an EV crossing over embedded Tx coils located within the road surface. The Rx coils, shown beneath the car, are illustrated as having two main spatial alterations: lateral positioning (a horizontal movement from the midline) and a vertical gap (air space between Tx and Rx). Magnetic coupling heavily relies on these parameters and, in turn, impacts the PTE. This illustration clarifies the inverse relationship between the extent of misalignment and PTE, highlighting the system's vulnerability to spatial discrepancies.

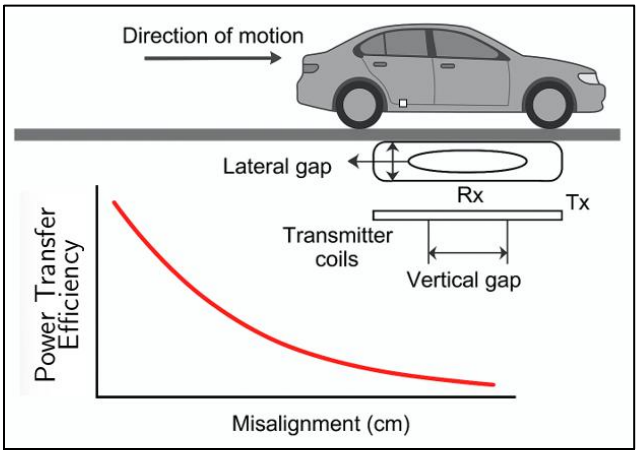


Figure 1. Misalignment Issues in DWPT

This paper examines the application of Gaussian curve fitting to determine lateral displacement based on measurements from the Rx coils. The outlined procedure demonstrates a cost-efficient and straightforward method for evaluating lateral misalignment. As compared to conventional methods, the proposed method eliminates the need for supplementary devices and demonstrates excellent adaptability for real-time operations. It offers a practical approach to maximise PTE under misalignment conditions, hence enhancing the robustness and effectiveness of DWPT systems.

II. LITERATURE REVIEW

Extensive research has been conducted to mitigate the effects of lateral displacement in DWPT systems. A three-coil topology has been reported to tolerate lateral misalignment of up to 20 cm (Ramakrishnan, 2024). The method reduces coil loss and leakage flux by approximately 40% using current distribution among overlapping rectangular coils (Ramakrishnan, 2024). In contrast, single Tx coil designs have also been introduced to stabilise magnetic field distribution over various distances without requiring extra control circuits (Pham *et al.*, 2023). ANN-based methods have also been applied to estimate mutual inductance under misalignment conditions (Goncalo *et al.*, 2024). Vertical misalignment, while a different form of displacement, also presents substantial performance degradation. Reconfigurable coil topologies have therefore been investigated, with reported efficiencies above 86.6% under 40% lateral misalignment (Ramakrishnan *et al.*, 2025). Such methods have reported PTE improvements of up to 12.4% (Tomoaki *et al.*, 2022). Figure 2 illustrates a typical WPT system integrated with a sensorless mutual inductance estimation loop. Voltage or current data from the WPT coils are processed to estimate misalignment. To validate these techniques, hardware experiments have been conducted under varied environmental conditions (Mo *et al.*, 2024; Ding *et al.*, 2025). For example, nine discrete lateral positions, ranging from 15 mm to 75 mm, were tested to evaluate the repeatability and reliability of the sensorless estimation method.

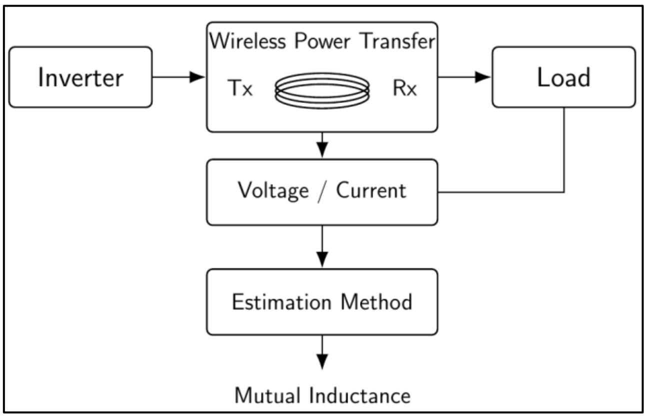


Figure 2. Block diagram of a typical WPT system integrated with sensorless mutual inductance estimation control

Researchers have also explored alternative coil designs, such as double-D, quadrature, and hybrid arrangements, for improved tolerance against misalignment (Lee *et al.*, 2023; Chen & Pan, 2022). To facilitate real-time estimation, curve-fitting algorithms have been employed to model mutual inductance and current profiles. Non-linear least squares and Kalman filtering have also been employed to improve estimation robustness and reduce measurement noise (Mo *et al.*, 2024; Kosik & Aaron, 2022). Artificial intelligence techniques have also been explored to improve estimation adaptability under varying operating conditions (Qian *et al.*, 2021). Circular coils remain widely used due to their structural simplicity and favourable tolerance to rotational misalignment (Covic & Boys, 2013; Jeshma & George, 2020; Budhia *et al.*, 2011; Patil *et al.*, 2015). Recent studies have further refined circular coil designs through numerical optimisation and finite element analysis (Covic & Boys, 2013; Jeshma & George, 2020; Budhia *et al.*, 2011; Patil *et al.*, 2015). Table 1 presents a range of methodologies used to address lateral displacement challenges in DWPT, with a particular focus on coil configurations and sensorless detection strategies (Aznavi *et al.*, 2020).

Table 1. Comparison of Coil Topologies for Lateral Misalignment in DWPT Systems

Coil Topologies			
Topology / Method	Key Features	Advantages	Disadvantages
Three-Coil Topology (Ramakrishnan, 2024)	Uses three overlapping rectangular coils with a current distribution strategy	- High lateral tolerance (up to 20 cm) - 40% reduction in leakage flux - Single capacitor (low cost)	Complex coil structure; Primarily suited for fixed config.
Single Tx Coil Design (Pham *et al.*, 2023)	Uniform magnetic field generation without extra circuitry	- Stable across varying distances - Simpler constr. - Lower cost	- Less effective for large misalignments - May lack fine-tuned adaptability
Reconfigurable Coil Topologies (Ramakrishnan *et al.*, 2025)	Dynamically adjust coil connections or paths	- High PTE (>86.6%) under 40% misalign.	- Requires control logic - Increased design complexity
Special Coil Geom. (Double-D, Quadrature, Hybrid) (Lee *et al.*, 2023; Chen & Pan, 2022)	Structural enhancements to improve alignment tolerance	- Tailored magnetic field shaping - Helps benchmark misalignment tolerance	- Design-specific - May not be generalisable or scalable
Circular Coils (Covic & Boys, 2013; Jeshma & George, 2020; Budhia *et al.*, 2011; Patil *et al.*, 2015)	Symmetric geometry redesigned for high-frequency WPT (20–150 kHz)	- Easy to manufac. - Tolerant to rotation - Improved with FEM based optimisation	Less robust to lateral shifts without modification
Alignment and Detection Methods			
Topology / Method	Key Features	Advantages	Disadvantages
Data-Based; Artificial Neural Networks (ANNs) (Goncalo *et al.*, 2024; Qian *et al.*, 2021)	Uses sensing coils with magnetic field data fusion	- Enables sensorless detection - Adaptive learning for misalignment patterns	Requires training data; Computationally demanding for real-time use
Sensorless Mutual Inductance Estimation Model	DC Current-Based Mutual Inductance Estimation.	- No extra sensors - Up to 12.4% efficiency gain	- Accuracy depends on a pre-defined lookup table.

(Tomoaki *et al.*, 2022; Ding *et al.*, 2025)		- Validated in experiments	- Multiple parameters in the mutual inductance estimation equation may reduce the robustness of this method.
Model-Based (e.g., Time-Domain Modelling, Nonlinear Least Squares) (Mo *et al.*, 2024; Kosik & Aaron, 2022)	Can determine the approximate lateral displacement based on the measured mutual inductance value	High accuracy and does not require additional supplementary equipment.	- No details on power levels or specific operational scenarios. - Only focuses specifically on mutual inductance estimation but does not determine or measure lateral displacement.

Coil improvement methods provide advantages in lateral tolerance, PTE, and system compliance. However, these methods introduce design-specific complexities, including structural limitations and increased control requirements. Even high-tolerance configurations, such as reconfigurable coils or double-D geometries, do not fully mitigate the effects of lateral misalignment, which continues to degrade performance. Additional alignment detection and misalignment estimation methods, including model-based and data-driven approaches, have been developed. Data-driven approaches can provide adaptive estimation capabilities but often require substantial computational resources and training data. Model-based approaches achieve high accuracy but are often unsuitable for real-time implementation and have limited integration with actual displacement estimation. A sensorless mutual inductance estimation model has also been reported with experimentally validated performance improvements (Tomoaki *et al.*, 2022). However, its reliance on predefined lookup tables and sensitivity to multiple parameters reduces its robustness and scalability. To address these limitations, a Gaussian fitting approach was selected. This method fits experimentally measured Irms current versus lateral displacement data to a Gaussian function, resulting in a smoother and more interpretable estimation process that is less dependent on rigid lookup tables. The Gaussian profile corresponds to the typical mutual inductance decay observed in circular and some rectangular coil geometries. The Gaussian model also enables interpolation between measured points and can be extended to account for vertical misalignment or other system variations. The resulting model provides a computationally efficient alternative to machine-learning and lookup-table-based estimation methods while maintaining suitability for real-time implementation. Table 2 summarises the key features, advantages, and limitations of the Gaussian fitting approach in DWPT systems.

Table 2. Proposed method for Lateral Estimation

Gaussian Fitting Approach for Lateral Estimation

Topology / Method	Key Features	Advantages	Disadvantages
Gaussian Fitting Approach for Lateral Estimation	Models the relationship between mutual inductance and lateral displacement using a fitted Gaussian curve derived from experimental data	Simple implementation, supports interpolation, adaptable to various coil shapes, and enables real-time estimation without additional sensors. Possible to	May need retraining for different setups or environments

	estimate the vertical gap of the system.

III. MODELLING APPROACH

This paper uses a Gaussian curve fitting method to uncover the relationship between lateral displacement and a circular coil WPT system. The Irms current at the Rx coil was chosen as the primary measurement variable because it directly reflects the amount of power effectively delivered under resonant conditions. Measurements were then taken at different lateral offsets while keeping the vertical coil distance fixed. Given that lateral displacement induces fluctuations in the magnetic coupling between the Tx and Rx coils, Irms functions as a dependable metric for assessing the alignment of the coils and the efficiency of power transfer. The resulting Irms versus lateral displacement data demonstrated a symmetrical bell-shaped distribution, attaining a peak at the midpoint (x = 0), which correlates with maximal coupling (optimal alignment). Displacing the Rx coil to the side of the Tx coil can cause a decline in magnetic coupling, eventually reducing the efficiency of power transfer. This behaviour underlines the importance of precise alignment in maximising the performance of the WPT system. The Irms data were subsequently modelled using the following Gaussian framework, as given in Eq. 1, which is a widely used function in experimental sciences for representing peak-shaped responses (Philip & Keith, 2003).

$$I_{rms}(x) = A.exp\,(-\frac{(x-B)^2}{2\sigma^2}) \qquad (1)$$

Where:

i. A is the peak current amplitude (maximum Irms when coils are aligned).
ii. B represents the lateral displacement corresponding to peak alignment (ideally 0).
iii. σ (standard deviation) representing how sensitive the system is to lateral misalignment (larger value indicates greater tolerance).
iv. x represents the lateral displacement in centimetres (cm).

This model was then applied separately for each vertical gap (2.5 cm, 3.5 cm, 4.5 cm, 5.5 cm) to extract unique A, B, and σ values. These parameters describe how the coupling profile changes as the vertical separation increases. Once the forward Gaussian model is determined, the inverse function can be used to estimate the lateral displacement based on a measured Irms value. This enables a form of real-time misalignment estimation, proper in DWPT systems for alignment correction or efficiency prediction.

From Eq. 1, the inverse model will result in:

$$x^{\circ} = \pm\sigma\sqrt{-2ln\left(\frac{I_{rms}-B}{A}\right)} \qquad (2)$$

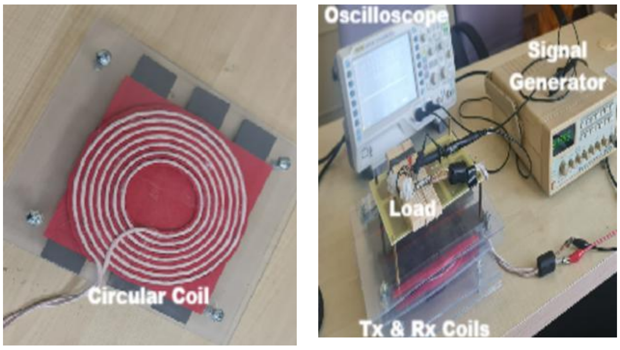
This model assumes symmetry and allows prediction of coil position using current as the input parameter.
The fitting procedure can be summarised as follows:

i. Data Collection: Measure Irms at each lateral displacement point under a constant vertical gap.
ii. Curve Fitting: Apply Gaussian fitting in MATLAB to determine A, B, and σ.
iii. Model Validation: Evaluate fit accuracy and verify prediction accuracy with additional test data.
iv. Application: Use inverse Gaussian to estimate position from Irms data.

By modelling lateral displacement using this approach, it becomes possible to decouple spatial misalignment information from current measurements without the need for vision or mechanical sensors.

A. Experimental Setup

As shown in Fig. 3(a), this paper utilises circular Litz wire coils with a diameter of 16 cm and seven turns. The coils are wound using Elektrisola Litz wire (660 strands × 0.10 mm, Grade 1, Polysole P155sp), chosen to minimise skin and proximity effects during high-frequency operation.



(a) **(b)**

Figure 3. Experimental Setup: (a) Transmitter and receiver circular coil assembly fixed on acrylic plates to control lateral displacement and gap height. (b) Complete measurement setup including signal generator (input), transmitter (Tx) and receiver (Rx) coils, resistor load, and oscilloscope for current/voltage monitoring.

A signal generator provides a continuous sine-wave to the Tx coil, operating at resonance frequencies for each tested air gap. The tested frequency range is from 100 kHz to 4.0 MHz, and the Rx coil is terminated with a 51 Ω purely resistive load. The experimental configuration, including the oscilloscope and measurement probes, is illustrated in Fig. 3(b). Lateral misalignment is introduced manually across a displacement range of −10 cm to +10 cm in 1 cm intervals. Vertical coil separations (air gaps) are tested at 2.5 cm, 3.5 cm, 4.5 cm, and 5.5 cm. For each displacement and gap combination, the voltage peak-to-peak voltage (Vpp) and Irms are recorded. Table 3 shows the parameters used in this paper. The 16 cm diameter and 7-turn coil design ensures a practical balance between magnetic coupling strength and spatial resolution. The use of ceramic capacitors tuned to a resonance near 900 kHz to 1 MHz enables efficient energy transfer in the near field. These parameters were selected to mimic realistic EV coil dimensions and behaviour.

Table 3. Parameter Setup

Components	**Values / Type**
Coil Type	Circular – Litz Wire
Diameter	16cm
No. of Turns (N)	7
Resonance Cap.	600pF / Ceramic
Resonance Freq.	900 kHz – 1MHz
Load (R)	51 ohms
Signal Type	Sinewave
Lateral Gap	0 – 10cm
Vertical Gap	2.5 – 4.5cm

Fig. 4 shows the flowchart based on the methodological framework of the proposed Gaussian-based lateral displacement estimation. Initially, a reliable vertical separation is created between the coils of the transmitter and receiver. Irms current measurements are obtained across a spectrum of lateral displacements. Thereafter, a Gaussian fitting strategy is implemented to illustrate the current profile, hence deriving key parameters (A, B, σ). The fitted model is validated using supplementary data to assess its predictive accuracy. Finally, the inverse Gaussian function is utilised to estimate lateral displacement from current measurements, with the outcomes compared against actual positions to determine the effectiveness of the performance.

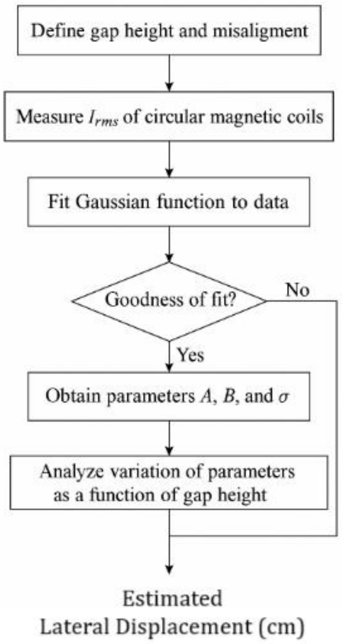


Figure 4. The flowchart of the proposed methodology for parameter estimation. The procedure involves defining gap height and coil misalignment, measuring the RMS current of the circular coils, fitting Gaussian functions to the measured data, and extracting parameters (A: peak amplitude, B: baseline offset, σ: standard deviation). The variation of these parameters with respect to gap height is then analysed to estimate lateral displacement

IV. RESULT AND DISCUSSION

The proposed Gaussian-based model demonstrates high accuracy and robustness in characterising the relationship between lateral displacement and Irms current in a circular WPT system across varying air gaps. Experimental measurements reveal that as the vertical separation between the Tx and Rx coils increases, the peak Irms consistently decreases. For instance, at a 2.5 cm air gap, the maximum current exceeds 0.055 A, while at 5.5 cm, the peak value drops to approximately 0.036A – 0.037 A. This trend aligns with theoretical expectations (Goncalo *et. al.*, 2024), where increased coil separation weakens magnetic coupling and thereby reduces PTE. The Irms current profiles across different lateral displacements for various air gaps are illustrated in Fig. 5. This figure also compares the distribution patterns at four separation distances (2.5 cm, 3.5 cm, 4.5 cm, and 5.5 cm), highlighting how the air gap affects both the peak current and the overall profile shape.

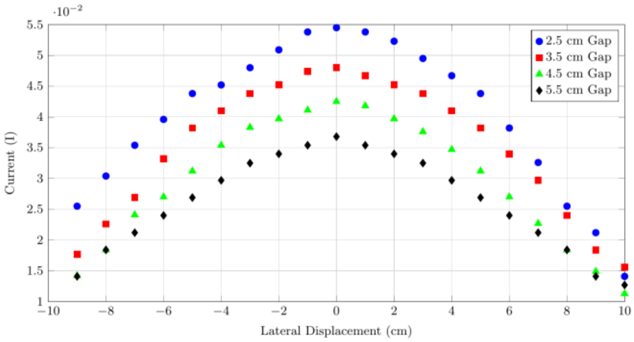


Figure 5. Irms Current Response vs Lateral Displacement for Various Air Gaps in a Circular Coil

Table 4 outlines the estimated Gaussian parameters, including amplitude (A), centre offset (B), and standard deviation (σ), which were derived through the process of curve fitting applied to the experimental Irms data. These metrics provide a quantitative overview of the structure of each response profile, thereby facilitating a systematic evaluation across diverse coil distances.

Table 4. Estimated Gaussian Parameters

***Z* (cm)**	***A***	***B***	***σ***
2.5	0.0545	-0.24	6.96
3.5	0.0484	0.0933	6.71
4.5	0.0425	-0.0075	6.25
5.5	0.03086	0.0063	7.95

In addition to peak current reduction, the spatial profile of Irms across lateral displacement widens with increasing air gap. This is quantitatively reflected in the parameter σ. While σ shows a decreasing trend from 2.5 cm to 4.5 cm, it increases significantly at 5.5 cm, suggesting a more diffuse magnetic field at larger air gaps. The 2.5 cm profile exhibits a sharp peak and a rapid current drop-off beyond ±4 cm displacement, highlighting strong coupling and a tightly focused magnetic field. In contrast, the 4.5 cm and 5.5 cm gaps exhibit broader profiles, indicating that the magnetic field becomes more dispersed at greater coil separations. All current distributions exhibit a precise Gaussian-like shape and are symmetric about the central axis (0 cm displacement), with the peak Irms consistently occurring at the origin. This symmetry implies precise coil alignment during measurement and is further confirmed by the near-zero parameter B values observed in the Gaussian fits. The repeatability of the shape across multiple gaps suggests that the experimental setup was consistently controlled. To evaluate the model's ability to reverse-engineer lateral displacement from measured Irms, Fig. 6 compares the actual lateral displacement against the values estimated using the inverse Gaussian function across all four air gaps.

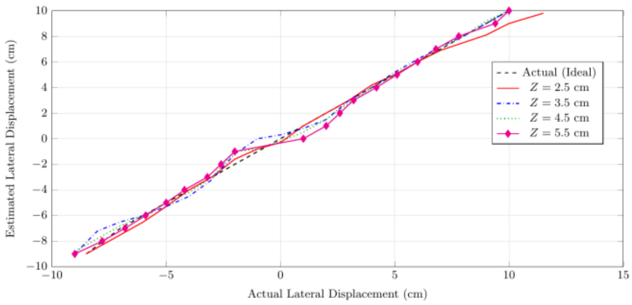


Figure 6. Actual vs Estimated Lateral Displacement

The findings prove that the approximated values closely correspond to the empirical measurements, especially in proximity to the centre, with progressively larger deviations observed at greater displacements. To assess how accurate the proposed technique for lateral displacement, a comparative analysis was executed across four distinct vertical coil separations: 2.5 cm, 3.5 cm, 4.5 cm, and 5.5 cm. The metrics of error associated with displacement values are displayed in Table 5, which features the mean absolute error (MAE), the highest absolute error, and the percentage difference range between estimated and actual values. The results show a noticeable performance trend: as the vertical separation increases, the accuracy of estimation enhances.

The minimal average deviation was recorded at a 5.5 cm gap, wherein the MAE and percentage difference were diminished to 0.33 cm and 0.2–7.34%, respectively. Conversely, the 2.5 cm gap displayed the most significant estimation error, with a maximum deviation of 1.43 cm and percentage differences soaring to 28.5%. This implies that wider coil separations create a more uniform mutual inductance characteristic, consequently improving the robustness of the inverse Gaussian fitting model. The results highlight the importance of carefully selecting coil spacing, which plays a crucial role in enhancing WPT efficiency and refining the accuracy of sensorless misalignment detection. The consistency of each estimation was assessed by calculating the mean percentage difference across all data points.

Table 5. Error Metrics for Lateral Displacement using Gaussian Model at Different Vertical Gap

Gap (cm)	Mean Absolute Error (cm)	Max Error (cm)	% Difference Range
2.5	0.36	1.43	0.5 – 28.5%
3.5	0.29	0.71	1 – 19%
4.5	0.18	0.67	0.3 – 17.5%
5.5	0.33	0.97	0.2 – 7.34%

As summarised in Table 6, the Gaussian model produced an average percentage difference of:

Table 6. Error Metrics for Lateral Displacement using Gaussian Model at Different Vertical Gap

Z (cm)	Average Percentage Differences (%)
2.5	14.5
3.5	10.00
4.5	8.9
5.5	3.77

The experimental results indicate that the best estimation performance was achieved at 5.5 cm, while estimation at 2.5 cm exhibited the highest deviation, which can be attributed to the flatter Irms profile and increased parameter interpolation uncertainty. These findings validate the utility of the inverse Gaussian model in estimating lateral position based on current response, even under varying air gaps. Although the accuracy decreases slightly at higher separations, the method remains robust and computationally efficient, with promising application in real-time alignment detection for misalignment-tolerant DWPT systems.

V. CONCLUSION

In conclusion, this paper presents a sensorless method for estimating lateral displacement using a Gaussian-fitted model. The output Irms current was the only parameter used, with an average percentage difference between 3.77% and 14.5%. In practical scenarios, lateral misalignment is an unavoidable issue. The Gaussian fitting model, based solely on the Irms current, was successfully validated through experimental testing. The proposed method provides a straightforward and cost-effective approach for estimating coil displacement in real-time. Its effectiveness can be further enhanced when paired with vertical gap sensors such as Hall-effect sensors, infrared detectors, or inductive proximity sensors. Alternatively, by using a lookup table constructed from Gaussian profiles at known air gaps, displacement can be estimated through interpolation, avoiding the need for additional height-sensing hardware altogether. This approach offers a valuable path toward controlling misalignment in actual DWPT systems.

However, there is a noticeable drawback where Gaussian-based fitting models typically rely on offline training and may require recalibration if the system setup changes. This can be impractical in applications where flexibility or scalability is needed. To address this, future work will explore adaptive modelling strategies that can either self-calibrate or learn continuously during operation, reducing the dependency on setup-specific pre-training. Overall, this paper presents a systematic modelling method based on Gaussian fitting for circular coil WPT systems, with an emphasis on practical, sensorless displacement estimation.

The findings provide a foundation for more responsive and adaptive DWPT designs. Moving forward, the focus will shift toward validating the model in dynamic scenarios and embedding it within closed-loop control schemes for real-time correction and improved reliability in vehicle charging applications.

VI. ACKNOWLEDGEMENT

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