An Analytical-based Optimization Method for Lift-off Effects in Transmitter-Receiver Eddy Current Probes

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Abstract

The lift-off effect is a main challenge for the eddy current testing (ECT)-based rail detections. The non-coaxial transmitter-receiver (TR) probes are considered as promising structures, however, the research focused on the transmitter-receiver coil distance optimization is limited. In this study, this coil distance is optimized for the Tx-Rx probe with varying lift-offs in rail inspections. Analytical simulations under different conditions show that the optimized coil distance can reduce the lift-off effect. The proposed method provides an optimization method for coil parameter design.

1 Introduction

Rail inspection is important in railway maintenance. Eddy current testing (ECT), especially, pulsed eddy current testing (PECT) is a viable method, as it has relatively higher inspection speeds and the surface defects detection ability [1]. However, the PECT probe will inevitably shake in the field test which will cause lift-off fluctuation. The lift-off is the distance between the probe and the rail, and the masked defect signal from the lift-off is one of the main obstacles for PECT [2]. Which is called the lift-off effect. Thus, to improve the detection accuracy, the lift-off effect of PECT in rail detection should be investigated. Non-coaxial transmitter-receiver (TR)-based probes are considered as promising structures to settle the lift-off problems, because of its high flexibility and spatial resolution [3]. Ona et al. [4] proved the detection sensitivity of the Tx-Rx probe can be affected by the coil distance and probe lift-off effect through numerical simulations and experiments. However, very few researchers investigate the coil distance variations to the lift-off effect and optimize the distance. In this study, based on the theoretical analysis of the Tx-Rx probe in reducing lift-off effects, the coil distance optimization method is given to adapt changes of lift-off in the rail inspection.

2 Analytical model

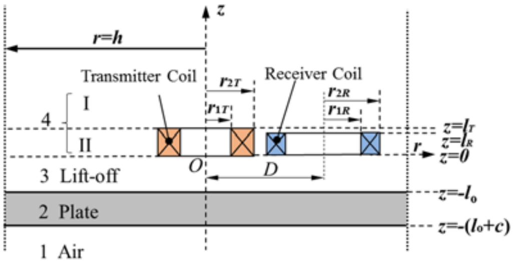


Fig. 1. A Tx-Rx probe over a three-layered structure.

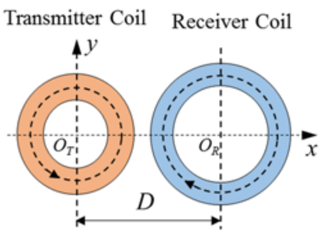


Fig. 2. A Tx-Rx probe in a polar coordinate.

As shown in Fig.1, the rail is approximated by a ferromagnetic metallic plate, the Tx-Rx probe with the lift-off of l_o located over the rail is simplified as a three-layered structure. The PECT signal can be derived from a sum of harmonic responses in the frequency domain by using an inverse Fourier transform (IFT). For each frequency component, according to Ref. [5], the induced voltage of the receiver coil $\triangle U$ can be expressed as:

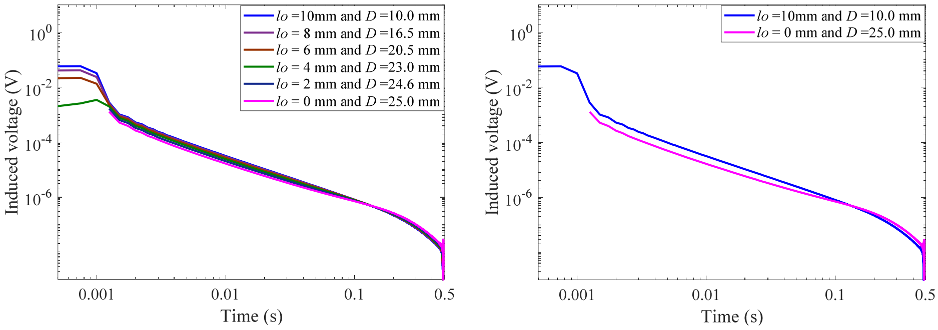
$$\Delta U = j\pi\omega\mu_0 I(\omega)\times\int_0^\infty e^{-2\alpha lo}\times J_0(\alpha D)\times S''(\alpha)R''_{4,3}(\alpha)\mathrm{d}\alpha \tag{1}$$

$$R''_{4,3}(\alpha)=\frac{(\mu_{r2}\alpha-\beta_2)(\mu_{r2}\alpha+\beta_2)-(\mu_{r2}\alpha-\beta_2)(\mu_{r2}\alpha+\beta_2)e^{-2\beta_2 c}}{(\mu_{r2}\alpha+\beta_2)(\mu_{r2}\alpha+\beta_2)-(\mu_{r2}\alpha-\beta_2)(\mu_{r2}\alpha-\beta_2)e^{-2\beta_2 c}} \tag{2}$$

$$S''(\alpha) = n_T n_R \frac{(e^{-\alpha l_R} - 1)}{\alpha l_{2R}} \frac{(e^{-\alpha l_T} - 1)}{\alpha l_{2T}} \times \frac{Int(\alpha r_{1T}, \alpha r_{2T})}{\alpha^2 (r_{2T} - r_{1T})} \frac{Int(\alpha r_{1R}, \alpha r_{2R})}{\alpha^2 (r_{2R} - r_{1R})} \tag{3}$$

where, D is the coil distance between the transmitter coil and the receiver coil, l_o is the lift-off, $J_0(x)$ denotes the zero-order Bessel function, $R''_{4,3}(\alpha)$ is the generalized reflection coefficient of the three-layered structure, $e^{-2\alpha lo}$ is defined as the lift-off coefficient, $S''(\alpha)$ is the spatial frequency spectra from the Tx-Rx probe, which gives the amplitude of the contributions as a function of wavenumber. Moreover, the analytical model has been verified experimentally in Ref. [5].

3 Conclusion



(a) (b)

Fig.1. Induced voltage $\triangle U$ of the Tx-Rx probe under various *lo* and *D*. (a) all the signals, (b) signals with lift-off=10 mm and 0 mm.

Equation (1) shows that $\triangle U$ is determined by three items: $R''_{4,3}(\alpha)$, $S''(\alpha)$, and $e^{-2\alpha lo} \times J_0(\alpha D)$. As l_o has no effect on $R''_{4,3}(\alpha)$ and $S''(\alpha)$, they will remain unchanged under various lift-offs. Therefore, if we also keep $e^{-2\alpha lo} \times J_0(\alpha D)$ in Equation (1) unchanged with various lift-offs through selecting an appropriate D, $\triangle U$ will remain the same. That is to say, the signals will not change with lift-off fluctuation through selecting an appropriate D, then the lift-off effect is eliminated.

To prove the Tx-Rx probe with the optimized coil distance is available for reducing the lift-off effect, signals under various l_o and D are given in Fig. 2. Wherein, the signals in Fig. 2(a) are obtained under different l_o and D. Two special signals under the maximum and minimum lift-offs are extracted from Fig. 2(a) to highlight the difference and are shown in Fig. 2(b). Results show that the difference of signals in Fig. 2(b) is smaller, especially at the later time of the signal. It demonstrates that the lift-off effect can be reduced by selecting D according to l_o–D integration and the probe lift-off.

Acknowledgements

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