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Analysis of sensor orientation in Railway axle counters, using Response Surface Methodology

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Abstract

Considering the importance of axle counter function in detecting the train wheels and determining the clearance or occupation of a track section, it is important to assure a safe and reliable performance of this system.

In this paper, in order to improve the sensor performance, the authors have focused on the orientation and position of magnetic sensors' coils.

In order to improve the measuring signal quality, in both situation of with and without wheel, it is important to adjust the relative orientation of the transmitter and receiver coils. Due to the existence of an infinite relative orientation of the sensor coils, RSM is applied in order to analyze the whole range of position and orientation of the system and introduce the optimum orientation. To provide some sample data, as inputs to the RSM algorithm, finite element modeling, FEM, approach is utilized.

The analysis not only provides the accurate relative orientation and positions of the sensor coils, it also improves the speed of analysis, comparing to absolute 3D FEM analysis and/or field based measurements.

Key words: electromagnetic sensor, Finite Element Method (FEM), Optimization, railway axle counter, Response Surface Methodology (RSM)

1. Introduction

Axle counter is one of the most important railway signaling devices, in detecting the train wheels and determining the clearance or occupation of a track section. The detector senses the wheels through evaluating the changes in the magnetic coupling between the coils placed at either rail sides.

With the increase of power-electronic systems and semiconductor devices usage in railcars, electromagnetic noises in the environment of railway lines are increasing (Ogawa et al., 2004). These noises may affect signaling systems mounted near the rail, like axle counters (Hill, 1997), and decrease their reliability. Therefore, in designing a signaling device, protection against the noises should be considered. The noise reduction is especially indispensable in the case of the axle counter, which is one of the most important railway signaling devices for accurate and safe train control systems (Otake et al., 2010).

In this paper, optimizing the orientation of magnetic sensors' coils to protect the axle counter against the noise is one of the goals.

Due to the existence of an infinite relative orientation of the sensor coils, Response Surface Methodology (RSM) is applied in order to analyze the whole range of orientation of the coils and introduce the optimum orientation.
RSM is a combination of mathematical and statistical techniques for empirical model building.
Duo to difficulties in testing the sensors in all possible positions and orientations, finite element modeling, FEM, approach is utilized. The data provided by FEM, is fed to RSM algorithm. Some numerical examples which demonstrate the effective proposed methods are also presented.

2.Railway Axle counter

An axle counter system is used for counting the number of train axles coming in and going out of a section of rail track. Axle counter makes use of electromagnetic flux linkage between two coils mounted on either side of the rail, to detect the passage of the wheels. The difference in the induced voltage in the receiving coil, in presence and absence of the wheel is detected and considered as passage of a wheel. The wheel detector detects the wheel when the amplitude of induced voltage in receiver is less than the threshold level, as shown in Fig. 1.
In order to reduce or eliminate the effect of noise on induced voltage, voltage amplitude difference in the presence and absence of a wheel (ΔV), should be as great as possible. Threshold level is considered at the middle of ΔV.

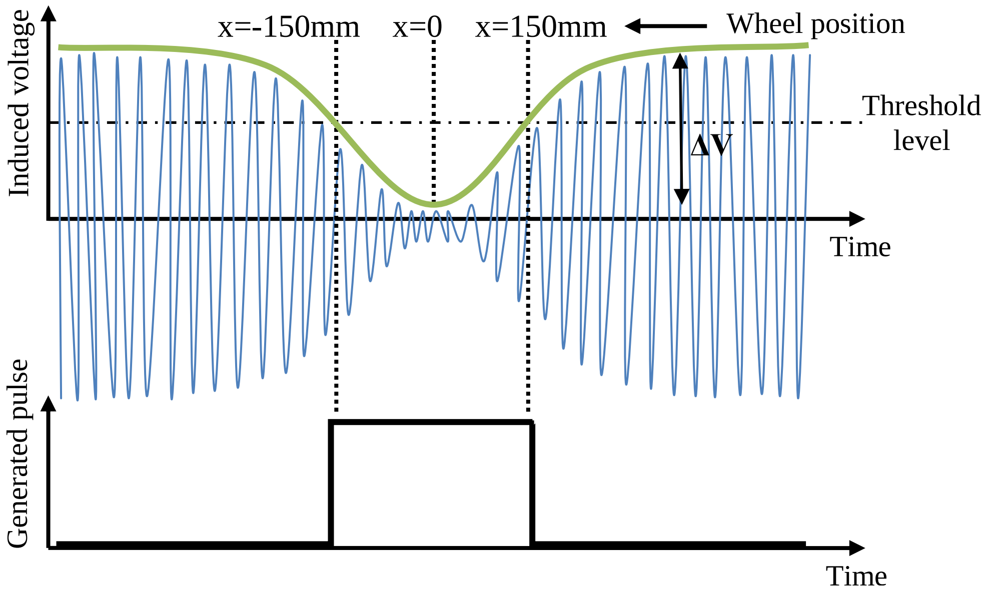

Fig 1: induced voltage and detecting principles

Having fixed the transmitter voltage, and frequency and also the number of coils' turns, induced voltage in the receiver depends on the relative orientation of the coils.

3. Research Methodology

Optimum orientation of sensors is where ΔV has its maximum value, in which the highest signal to noise ratio for a particular level of noise can be achieved.
In fact, greater ΔV, results in more sensor sensitivity to wheel and less sensitivity to noise.
The finite-element method (FEM) is used to calculate the induced voltage in receiving coil. Hexahedral and tetrahedral meshes are utilized and adequately are combined by using the method mentioned in Kameari (2008). In addition, when displacing the arrangement of

the coils, only the air region around the receiving coils are remeshed, to reduce the computational time for the mesh generation (Otake et al., 2010).

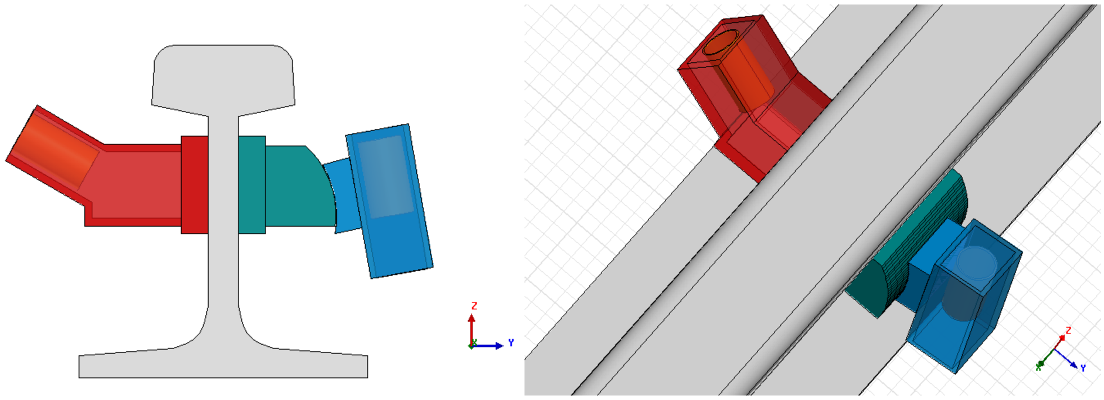

Fig 1: 3D axle counter model

In order to validate the used model in FEM, we compare measured and calculated induced voltages in some sensor arrangement (Table 1)

Induced voltage / Sensor orientation (Rx angle)	Calculated (mV)	Measured (mV)
-30deg	335	340
-20deg	409	400
-10deg	467	450
0deg	515	500
0deg (In presence of wheel)	79	85

Table 1. Comparison between measured and calculated induced voltage

For this optimization problem, ΔV considered as dependent variable (response), and receiver and transmitter coils' angles (θ_R and θ_T) considered as independent variables (inputs). Because of space limits around rail, θ_R can change between -80 to +20 degrees and θ_T can change between -20 to +80 degrees. (Fig. 3)

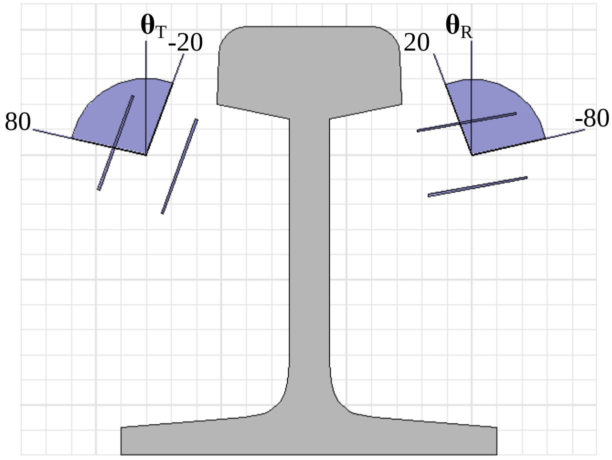

Fig 2: Design variable and search domain

RSM is used to optimize the design process, because of its ability for nonlinear regression and continuous processes modeling.

RSM is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables) (Montgomery, 2002).
The optimization process is estimating a function represent relationship between ΔV and θ_R and θ_T with RSM, and then finding the maximum value of this function that is optimal design point.
Generally, the structure of the relationship between the response and the independent variables is unknown. The first step in RSM is to find a suitable approximation to the true relationship. The most common forms are low-order polynomials (first or second-order).
To discover the structure of the relationship between response (ΔV) and independent variables (θ_R and θ_T), the variation of ΔV with change of each variable, since other is fixed, is measured. (Fig. 4)

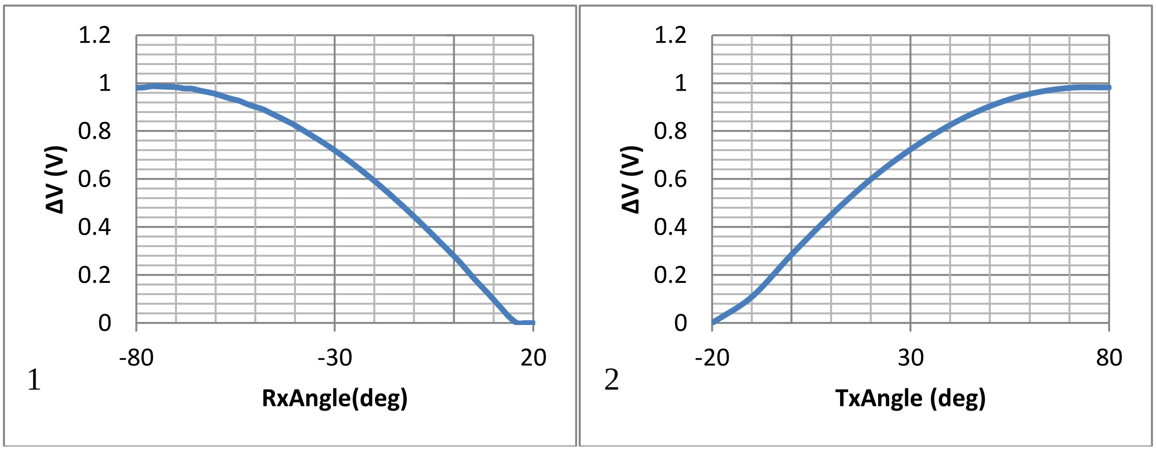

Fig 3: ΔV versus 1) receiver coil angle and 2) transmitter coil angle

These relations can be estimated as a two order function, like (1).

$$\Delta V = b_0 + b_1\theta_R + b_2\theta_T + b_3\theta_R^2 + b_4\theta_T^2 + \varepsilon \quad (1)$$

Where, ε represents the noise or error observed in the response ΔV and b_i's are the tuning parameters. We wish to find the vector of least squares estimators, b, that minimizes L.

$$L = \sum_{i=1}^{n} \varepsilon_i^2 = \varepsilon'\varepsilon = (\Delta V - Xb)'(\Delta V - Xb) \quad (2)$$

After some simplifications, the least squares estimator of b is

$$b = (X'X)^{-1} X'\Delta V \quad (3)$$

And the fitted regression model is

$$\Delta V_{RSM} = Xb \quad (4)$$

To construct an approximation model that can capture interactions between N design variables, a full factorial approach (Montgomery, 1995) may be necessary to investigate all possible combinations. A factorial experiment is an experimental strategy in which design variables are varied together, instead of one at a time.
By full factorial approach, 9 (=3^2) experiments is needed (Table 2).

Coded Variables		Virtual Variables		Response
θ_R	θ_T	θ_R(deg)	θ_T(deg)	ΔV(dBmV)
-1	-1	-80	-20	0.083524
-1	0	-30	30	0.880799
-1	1	20	80	1.04469
0	-1	-80	-20	0.086252
0	0	-30	30	0.744149
0	1	20	80	0.870408
1	-1	-80	-20	0.024925
1	0	-30	30	0.079133
1	1	20	80	0.071678

Table 2. Full factorial experimental design

4. Results and Analysis

After implementation of experiments, approximated function is:

$$\Delta V_{\text{RSM}} = 19.8151 - 0.1848\theta_R + 0.1739\theta_T - 0.0015\theta_R^2 - 0.0014\theta_T^2 \tag{5}$$

Fig. 5 illustrates this function.

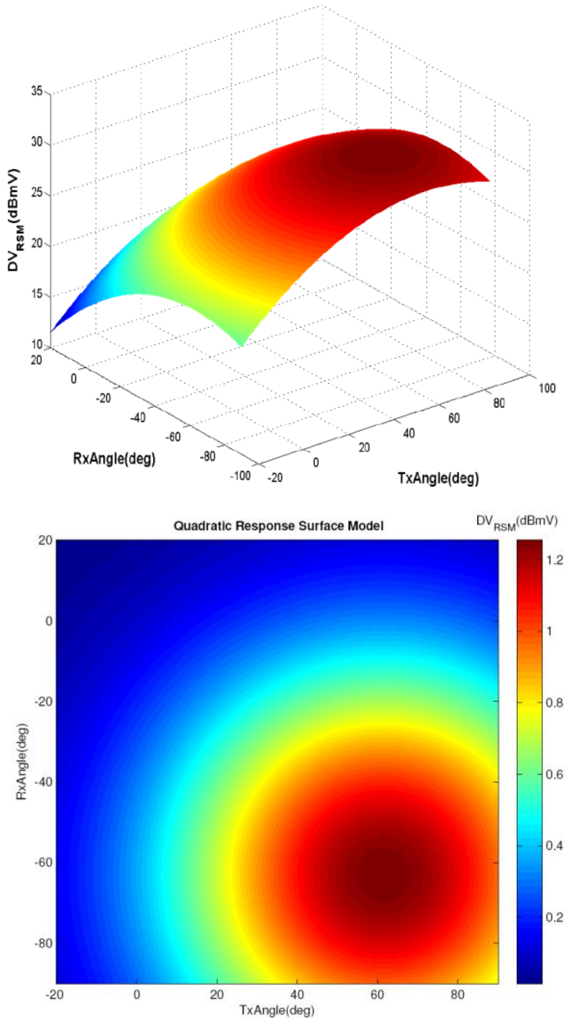

Fig 4: quadratic response surface of ΔV_{RSM}

Maximum value of this function is 1.25 Volts in (θ_R, θ_T) = (-61.6deg, 62.1deg).
In order to confirm the accuracy of RSM, the calculation results of the RSM and that of the FEM analysis are compared in Fig. 6.

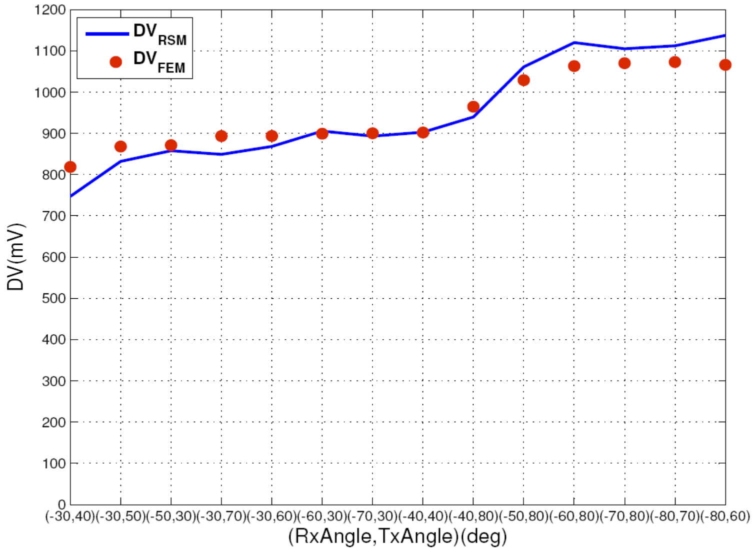

Fig 5: Accuracy validation of RSM

By placing real system sensors in obtained orientations, induced voltage difference is 1.1 volts, which is the maximum voltage induced in receiver coil.

5. Conclusions

In this paper, combination of FEM and RSM approaches are used to optimize railway axle counter sensors orientation, which is more insusceptible to electromagnetic noise than initial arrangement. The FEM is used to calculate the electromagnetic flux and induced voltage in receiving coil. The RSM is used to optimize sensors orientation, and clarify the effectiveness of reducing the computational burden in estimating and optimization process.
As the result, the maximum induced voltage difference is achieved at the optimized arrangement, which results reducing the effect of electromagnetic noise in railway axle counter sensor.

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