Neural Network Based Temperature Field Mapping Model for CRTS II Type Ballastless Track

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Abstract. In order to investigate the mapping relationship between the meteorological parameters and the internal temperature field of the track plate, this paper takes the CRTS II type ballastless track of a passenger dedicated line in East China as the research object, and builds an on-line monitoring system for the temperature field of the intelligent track plate, and carries out real-time data on the ambient temperature, solar radiation, wind speed and the internal temperature of the track plate. Based on the BP neural network method, the variation rule of the temperature field inside the track plate is studied, and the mapping relationship between the environmental meteorological parameters and the temperature of the track plate is established. The prediction results show that the prediction accuracy of the nonlinear mapping model is 92.4% and the prediction accuracy of the temperature gradient is 81.5%, and the prediction accuracy is 96% and 93% respectively for the 13:00-16:00 time section of the overall temperature and the maximum positive temperature gradient of the track plate.

1. Introduction
Ballastless track structure is a multi-layer continuous band structure composed of reinforced concrete. The ballastless track is exposed to the atmosphere for a long time, and bears the environmental temperature, solar radiation and wind speed and other environmental factors. In the process of heat exchange with the outside world, due to the poor thermal conductivity and volume sensitive material, the temperature field of track plate structure is nonlinear. Different from the ballastless track plate, the longitudinal continuous ballastless track plate will produce large deformation and stress under the action of temperature load. The overall temperature of the track plate will be uniformly raised and down to make the track plate produce the whole expansion deformation, but because of the poor thermal conductivity of the concrete structure, the track plate has a temperature change along its thickness direction. The temperature gradient is the main cause of the defects such as the warping deformation of the track plate and the off seams of the bottom of the plate [1-3], which seriously affects the structural stability and service performance of the ballastless track, and directly threatens the safe operation of the train.

At present, the test and analysis of the temperature field of ballastless track under different conditions have made some achievements. SenRong Wang [4] measured the temperature of the rail plate by placing the plate overhead on the board and simulated the warpage stress of the track plate according to the measurement results. Yu Liu [5] made a long-term field observation on the early longitudinal connection stage of the CRTS II type ballastless track at Beijing-Shanghai high-speed...
railway. Based on the least square method, the prediction model of the surface temperature of the track plate was established. ZuMin Ou [6] used the meteorological data to describe the boundary conditions of environmental factors based on the heat transfer theory, established the temperature field equation of the ballastless track structure in the atmospheric environment, and analyzed the temperature distribution of the track structure caused by the changes of meteorological data. At present, although there are some research results in the temperature monitoring experiment and temperature field analysis of ballastless track, there are still some limitations. On the one hand, there are few studies on the combination of the measured ballastless track temperature measured by the actual operating high-speed rail line and the field weather data around the line. On the other hand, a large number of thermal parameters are involved in the theory of heat conduction analysis. There are many assumptions and simplification conditions, and the key parameters are difficult to apply to the environment complex. Study on the temperature field of ballastless track in mixed and changeable areas. Therefore, the monitoring and analysis of the internal temperature of the track structure and the meteorological data around the line is of great significance to the study of the mapping relationship between the meteorological parameters and the internal temperature field in the ballastless track, the accurate analysis of the distribution of the temperature field inside the track and the calculation of the temperature stress of the ballastless track.

In order to study the mapping relationship between environmental meteorological parameters and temperature field of CRTS II type ballastless track structure under service condition, The CRTS II type ballastless track of a passenger dedicated line in East China is taken as the research object in this paper. Based on BP neural network, the mapping model of temperature field of environmental meteorological parameters and ballastless track structure is set up. The validity and accuracy of the temperature field mapping model of ballastless track structure are verified by the field measured temperature distribution data. It can provide theoretical reference and data support for structural parameter design and maintenance plan of high-speed railway ballastless track.

2. Temperature field monitoring of CRTS II type slab ballastless track
The monitoring site is located on a dedicated passenger line in East China. The line operates at a speed of 300 km/h. This area belongs to the north subtropical monsoon climate zone. Due to the alternating cold and warm air, the weather is complex and changeable. The selected time for this monitoring is from June 2017 to August 2017, which is the summer high temperature weather in East China. The monitoring contents include ambient temperature (℃), solar radiation (W/m2), wind speed (m/s), and temperature inside the track plate (℃). According to the actual line operation requirements, by establishing a track plate temperature field test equipment, synchronous real-time on-line monitoring of the meteorological parameters around the operating line and the internal temperature of the CRTSII type track plate was realized. While satisfying the requirements of the test, the number of sensors should be as small as possible to reduce the impact of the installation of the sensor on the performance of the track structure. The monitoring system framework is shown in figure 1.

![Figure 1. frame chart of monitoring system](image1)

![Figure 2. Measurement Points layout](image2)

The temperature measurement points inside the track plate should be located in the areas with larger stress and displacement of the track plate, and areas sensitive to temperature changes. The
temperature measurement points in the middle position of the track plate are selected, and the
temperature sensor is used for sampling, the measuring range is -20-150 ℃, and the measuring
accuracy is ±0.01 ℃. While satisfying the requirements of the test, the number of sensors should be as
small as possible to reduce the impact of the installation of the sensor on the performance of the track
structure. Therefore, three temperature sensors are arranged vertically along the track structure at a
certain depth interval, as shown in figure 2. The temperature is monitored at the depth of 20mm,
100mm and 180mm on the surface of the track plate. The temperature of 20mm and 180mm on the
upper surface of the track plate is used to analyze the vertical temperature gradient of the track plate.

\[
\frac{\Delta T}{\Delta y} = \frac{T(20) - T(180)}{y_{180} - y_{20}} = \frac{T_{20} - T_{180}}{y_{20} - y_{180}}
\]

(1)

In the formula, and are temperature from 20mm and 180mm on the surface of
track plate respectively and are the vertical distance from the upper surface of the track plate respectively. The temperature of 100mm on the upper surface of the track plate is used to analyze the overall
temperature variation of the track plate.

3. Monitoring data analysis

The analysis of monitoring data is shown in figure 3, which shows the amplitude of meteorological
data from June 2017 to August.

The temperature and solar radiation of the test site are all high, the solar radiation is up to
1136W/m², the maximum temperature of the environment is up to 43.7 ℃, and there is a large
temperature difference between day and night, and the overall wind speed amplitude is not changed
during the test. The overall wind speed is stable between 2–6m/s and the maximum wind speed is up
to 10.3m/s. During the monitoring period, the amplitudes of temperature and solar radiation fluctuated
more in June, and the amplitudes in July and August were relatively stable. At the end of August, there
was a trend of decreasing temperature in late summer, and the amplitude of solar radiation and
temperature showed a downward trend.

![Figure 3. Monitoring site amplitude statistics](image-url)

Based on the monitoring data of the weather station, the internal temperature of the track plate
structure on the day when the maximum ambient temperature of 43.7 ℃ during the monitoring period
was selected was used for data analysis. As shown in figure 4.
Figure 4. The variation of the temperature of the track plate and the ambient temperature

The change trend of the internal temperature and the ambient temperature of the track plate structure is basically the same, and the overall temperature of the track plate is high throughout the day. The maximum ambient temperature occurred at 14:00 on July 24, 2017, reaching 43.7°C, and the maximum temperature at the 20mm from the surface of the track plate exceeded 56°C on the day and was 12.61°C higher than the ambient temperature. During the day, the track plate absorbs heat from the outside world. The temperature at 20mm is higher than the temperature at 180mm. The night cooling track plate releases heat from inside to outside. The temperature at 180mm is higher than 20mm, and the minimum temperature at 180mm is 40.43°C.

Because of the low thermal conductivity of the concrete structure, the temperature has a slow transmission within the coagulant structure, and the time with the depth of the temperature extremum of different depth of the track plate increases with the depth. The minimum 20mm temperature on the track surface appears around 5:30, and the maximum value appears at 14:00. The minimum 180mm temperature on the surface of the track plate relative to 20mm appears at 7:30, which is about 2 hours behind. The maximum value appears at 16:30 or about 2.5 hours.

4. Mapping model of BP neural network

4.1 The principle and algorithm of BP neural network

Neural network is a widely parallel interconnection network composed of adaptive simple units, which can be used to deal with classification and fitting problems. At present, BP neural network algorithm is the most widely used network model. The BP network is a multi-layer feed-forward neural network. The full connection method is adopted between layers, and there is no mutual connection between the same layers. The hidden layer may have one or more layers. Ability to learn and store multidimensional input-output pattern mappings. The topological structure of BP neural network model includes input layer, hidden layer and output layer. The typical model is shown in figure 5.
The neural network learning adopts improved BP algorithm, and the learning process consists of forward calculation process and error back propagation process. In the forward calculation process, the input information is calculated layer by layer from the input layer through the hidden layer and passed to the output layer. The state of each layer of neurons only affects the state of the next layer of neurons. If the output layer can not get the desired output, then it goes to the process of error back propagation. The error signal returns along the original connecting path. By modifying the weights of the neurons in each layer, the network system error is minimized. In the end, the input and output mapping relationships that are desired to be established are approximated.

4.2 Mapping model construction

In heat transfer theory, there are mainly three kinds of heat transfer methods: conduction, convection, and radiation. The heat transfer modes on the surface of the track plate are mainly heat convection and heat radiation. Solar radiation is the main source of thermal radiation. The wind speed and the temperature affect the convective heat transfer on the surface of the track plate. The difference in the daily temperature is related to the highest and lowest temperature, which characterizes the radiation heat transfer intensity. Therefore, weather parameters such as ambient temperature, solar radiation, wind speed, and daily temperature difference are selected as input parameters, and the overall temperature and temperature gradient of the orbital plate are used as output parameters.

The 4225 track plate temperature data and corresponding meteorological parameters actually measured during the test period were integrated, of which 80% were used as training samples and the remaining 20% were used for test data. The raw data is normalized as follows before model training.

\[ x'_n = \frac{x_n - x_{r,\text{min}}}{x_{r,\text{max}} - x_{r,\text{min}}} \times (x_h - x_j) \] (2)

Here, \( x'_n \) : normalized input data, \( x_n \) : original data, \( x_{r,\text{max}}, x_{r,\text{min}} \) : maximum and minimum values for the input, \( x_h = 1 \), \( x_j = 0 \).

The BP learning method is used to train the neural network model. The training functions of trainlm, trainscg, trainrp and traincgb4 are used in turn, and the mean square error (MSE) and Pearson correlation coefficient (PCC) are used to evaluate the performance of the network. The number of neurons in the hidden layer is 4 based on the formula (3), and a neural network mapping model is set up. The number of iterations is set to 300 times.

\[ m = \sqrt{n + 1 + \alpha} \] (3)

\( m \): the number of hidden layer nodes, \( n \): the number of input layer nodes, \( l \): the number of nodes in the output layer, \( \alpha \): the integer between 1 and 10. Run the network randomly 5 times for training function, and get intermediate results, as shown in Table 1. The trainlm training function shows better network structure training ability, and the prediction results show a strong correlation with the measured values (0.8 < PCC<1.0).

| Serial number | Training function | MSE     | PCC    |
|---------------|-------------------|---------|--------|
| 1             | trainlm           | 0.018441| 0.9484 |
| 2             | trainscg          | 0.020609| 0.7427 |
| 3             | trainrp           | 0.021499| 0.6987 |
| 4             | traincgb          | 0.020467| 0.8044 |

The determination of the number of neurons in the neural network structure model is very important to the establishment of the model. Using the mean square error (MSE) to evaluate the network performance of the model to determine the number of neurons in the hidden layer. The number of hidden layer neurons varies in the range of 1~30.
As shown in figure 6, when the neural network model is trained, the mean square error of the `trainlm` training function varies with the number of neurons in the hidden layer. When the number of hidden neurons increases from 1 to 15, the mean-square error decreases rapidly. When the number of hidden neurons exceeds 22, the mean square error of the `trainlm` training function fluctuates significantly. When the number of neurons in the hidden layer increases from 1 to 30, the mean-square error is smallest when the number of hidden neurons is 25. When the number of neurons in the hidden layer exceeds 25, small fluctuations in the mean square error occur. Therefore, a 4-25-2 mapping model neural network structure as shown in figure 7 is established.

![Figure 6. The variation of MSE with the number of neurons in the hidden layer](image)

4.3 Mapping model validation

In order to verify the accuracy of the established mapping model, the test data was input into the trained model for calculation. The overall temperature prediction accuracy reached 92.4%, and the temperature gradient prediction accuracy reached 81.5%. Because the maximum overall temperature and the positive temperature gradient of ballastless track in our country generally appear in the 13:00-16:00 period of 5-8 months, the environmental meteorological parameters corresponding to the monitoring data of 13:00-16:00 are randomly selected into the established neural network mapping model. The prediction results are compared with the measured results, as shown in table 2.

| Time     | Forecast result /°C | Measured result /°C | Error /% | Forecast result /°C | Measured result /°C | Error /% |
|----------|---------------------|---------------------|----------|---------------------|---------------------|----------|
| 13:00    | 42.28128            | 44.21               | 4        | 52.15699            | 53.5                | 2        |
| 13:30    | 43.42063            | 45.09               | 3        | 53.26323            | 56.375              | 5        |
| 14:00    | 45.32934            | 45.61               | 0.6      | 51.71079            | 55                  | 5        |
| 14:30    | 42.16435            | 45.895              | 8        | 38.47776            | 41.1875             | 6        |

![Figure 7. Mapping model neural network structure](image)
### Time | Track slab overall temperature | Track slab temperature gradient
--- | --- | ---
15:00 | 44.21851 | 46.25 | 4 | 45.33099 | 49.125 | 7
15:30 | 45.66035 | 46.4 | 1.5 | 42.84183 | 45.375 | 5
16:00 | 45.02496 | 46.345 | 2 | 36.92999 | 40.0625 | 7

The neural network structure of the mapping model can accurately discover the nonlinear mapping relationship between meteorological parameters and the overall temperature and temperature gradient of the track plate.

### 5. Conclusions
1) This paper studies and analyzes the mapping relationship between environmental meteorological parameters and the temperature field of CRTS II type ballastless track structure in eastern China under service status, and draws the following conclusions:
2) An on-line temperature monitoring system for intelligent orbital plates was established to realize real-time simultaneous online monitoring of the temperature around the line and on the CRTS II type ballastless track;
3) In the high temperature weather conditions in East China, the interior temperature and the ambient temperature of the track plate structure are basically the same. Due to the low thermal conductivity of the concrete structure, there is a significant hysteresis at different moments when the extreme temperature of the track plate occurs.
4) Nonlinear Mapping Model of Temperature Field Inside Orbital Plate Based on BP Neural Network The prediction accuracy of the overall temperature reached 92.4%, and the accuracy of the temperature gradient prediction reached 81.5%. For the period from 13:00 to 16:00 when the extreme temperature of the orbital plate and the maximum positive temperature gradient occur, the prediction accuracy reaches 96% and 93%, respectively, which can meet the actual needs of the high-speed railway project.

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