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Rail temperatures models validated with experimental measurements

MODELOS DE TEMPERATURAS PARA CARRIS VALIDADOS COM MEDIÇÕES EXPERIMENTAIS

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abstract

Rail temperature plays an important role when understanding and predicting thermal buckling. An energy balance model called CNU was used to simulate rail temperatures, validated with FEA analysis, and compared with experimental measurements. The model uses weather data and accounts for the solar position and shadow effect to improve temperature prediction. Furthermore, a python package is developed to solve the thermal lumped model including specific modifications on the model. The results from the simplified model and Finite Element Analysis (FEA) model are in good agreement. Compared with the collected data, the model reaches the value R^2 of 0.914.

Keywords: Rail Temperature / Finite Element Analysis / Prediction Models

resumo

A temperatura dos carris de via férrea desempenha um papel importante ao compreender e prever as instabilidades térmicas. Foi utilizado o modelo CNU, baseado no balanço de energia, para simular a temperatura dos carris, validado com a análise por elementos finitos (FEA) e comparado com medições experimentais. O modelo utiliza dados meteorológicos e considera a posição solar e o efeito de sombra para melhorar a previsão da temperatura. Além disso, foi desenvolvido um programa em python para resolver o modelo de capacitância térmico, incluindo modificações específicas no modelo. Os resultados do modelo simplificado e do modelo de elementos finitos (FEA) estão de acordo. O modelo atinge um valor R^2 de 0,914, quando comparado com os resultados experimentais.

Palavras-chave: Temperatura do Carril / Método dos Elementos Finitos / Modelo de Previsão

1. INTRODUCTION

Railways are structures subject to various weather conditions such as rain, snow, solar radiation, and different ambient temperatures. These conditions make the rail temperature have a high amplitude of values during the time, often reaching extreme temperature limits. Furthermore, rail temperatures play an important role in the mechanical behavior of the track, and depending on the working boundary conditions, it can lead to failure. Lower temperatures may cause brittle failure, meanwhile, high temperatures may cause track buckling (Van, 1996).

Continuous Welded Rail (CWR's) are more likely to fail from thermal loads than jointed rails since there are no gaps to allow the track to expand or contract when temperature changes occur. Prevention measures are taken by rail operators when hot weather is forecasted. These measures consist of issuing speed restrictions, for example, in Australia the threshold air temperature is within the range of 38 °C to 43 °C (Wu et al., 2010). In addition, CWR's are getting common due to low maintenance costs when compared to traditional jointed tracks, thus track stability under different weather conditions rises a great concern. Many mechanical models have been developed to ensure track stability, whether by Finite Element Analysis (FEA) or analytical approaches, however, the next step on preventing rail failure is to predict the track instability before it happens (Wu et al., 2010).

Two approaches are used to forecast rail temperatures: empirical relations and physical models. Important empirical models were proposed in (Esveld, 2001) (Hunt, 1994) (Wu et al., 2010). Regarding physical modeling, it consists of understanding the thermal behavior of a rail track during the day and then modeling with energy balance and heat transfer equations. Notable models were developed by different authors (Chapman et al., 2008) (Hong et al., 2019) (Kesler & Zhang, 2007) (Zhang & Lee, 2008).

This paper is based on utilizing the model developed in Chungnam National University (CNU) by Hong *et. al* (Hong et al., 2019), which is an improved version of the thermodynamic model proposed by Zhang *et. al* (Zhang & Lee, 2008). The model consists of an energy balance equation for a rail segment, where three heat flow modes need to be considered: solar radiation absorption, convective heat transfer between rail and ambient, and radiation emissions from the rail segment to the ambient. The CNU focused on the improvement of the incoming solar radiation absorption, proposing a method to consider the sun's position on the model.

The goal of the present work is to use the CNU with special modifications, using python programming language, validate the solving process with FEA and validate the model with experimental measurements.

2- PREDICTION MODELS

The paper focuses on physical modeling by making small adaptations on the CNU model, which accounts for the energy exchange between the rail and its surroundings, considering the rail as a uniform temperature in the rail mass with unitary length. The incoming sun's radiation is the energy input of the model and the outgoing energy occurs due to convective heat transfer and radiation emission. These conditions are translated in Eq. (1) and Eq. (2) correlates the wind speed (w_s) and the convection coefficient (h_{conv}). These equations coupled together constitute a non-linear first-order differential equation.

$$\mathrm{SR} \cdot \alpha_s A_s - \left[h_{conv} A_c (T_{rail} - T_{air}) + \epsilon_{res} \sigma A_r \left(T_{rail}^4 - T_{sky}^4\right)\right] = \rho C V \frac{dT_{rail}}{dt} \tag{1}$$

$$h_{conv} = \begin{cases} 5.6 + 4w_s \,;\, w_s \leq 5\ ms^{-1} \\ 7.2 \cdot (w_s)^{0.78} \,;\, w_s > 5ms^{-1} \end{cases} \tag{2}$$

The parameters of the equation relate to material and surface properties, geometric constraints, weather information, and physical constants, which most of them are well characterized or can be measured, such as air temperature, solar radiation, and wind velocity. On the other hand, parameters such as material's solar absorptivity and emissivity are difficult to determine since it depends on the surface conditions and they are temperature and wavelength dependent. Common values of solar absorptivity for rail's steel fall into the range of 0.75 and 0.85 and emissivity 0.65 to 0.85 (Hong et al., 2019) (Zhang & Lee, 2008).

Hong *et. al.* (Hong et al., 2019) included the effect of different longitudes by proposing an assessment of the sun area parameter (A_s) making it time and geographical dependent. Since the sun follows a specific path during the day, see Fig. 1, and the latter changes of the year and for different positions on the globe, the approach is to correlate the shadow due to the sun's rays and the solar area (Fig. 2). Therefore, is necessary to calculate the sun's position for any given location and time, thus the authors make use of Michalsky's method to determine the solar azimuth and elevation (Fig. 1).

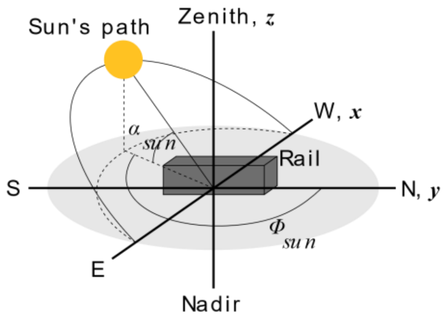

Fig. 1 | Rail position relative to the sun.

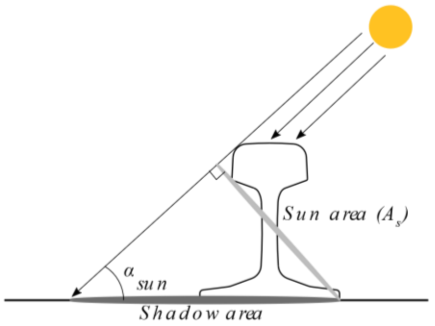

Fig. 2 | Relation between shadow and sun areas.

The shadow area is achieved by projecting onto the ground (XY plane) the vertices of a discrete cross-section of the rail using the sun's position as a direction vector and by utilizing Eq. 3 it is possible to calculate the area of the shadow (S_{shadow}),

$$S_{shwdow} = \frac{1}{2} \sum_{i=1}^{n} (x_i + x_{i+1})(y_i - y_{i+1}) \tag{3}$$

where (x_i, x_i) denotes the point's coordinates and n the number of points. Once the area is determined, it is possible to correlate it to the sun area (A_s) parameter with Eq. 4. A discrete rail section made of 14 vertices in each parallel face has been used.

$$A_s = S_{shadow} \sin \alpha_{sun} \tag{4}$$

Hong *et. al.* (Hong et al., 2019) reported a correlation factor between simulated and measured rail temperature of 0.93 when analyzing 200 days of collected data in a test rail track. In addition, the authors suggest that the model should be evaluated in other locations to further confirm its usability.

3. MATERIALS AND METHODS

3.1. Experimental measurements

Weather and rail temperature data were collected on a track in the city of Mirandela, located in the north of Portugal. The weather data consist of air temperature, solar radiation, and wind speed, all parameters needed to use the CNU model. The monitored rail section is made of UIC54 profiles with a metric gauge and the track is part of the deactivated Tua line. The rail temperature was measured with a set of 2 K-type thermocouples welded on the middle of the rail's web, as shown in Fig. 3 and Fig. 4.

3.2. Model's solution and adaptations

To solve the CNU model, a python package was developed containing all the necessary tools to solve the differential equation presented by the model. The package was developed with help of the core libraries: SciPy, NumPy, Pandas, and PySolar. In addition, the source code is available to download [1].

Modifications were made into the package to facilitate the solving process and the coding. First, instead of using Michalsky's method to calculate the solar position as described by Hong *et. al.* (Hong et al., 2019), the package makes use of the PySolar library, which has its methods to calculate the solar elevation and azimuth at any given time and position. The algorithm is described

Fig. 3 | Sensors of the rail.

Fig. 4 | Installation of thermocouples.

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[1] Source code available in: https://github.com/aryvini/railtemp

in (Reda & Andreas, 2008). Second, a built-in algorithm of the SciPy core library called *scipy.spatial.ConvexHull* was used to calculate the shadow area after projecting the vertex of the discretized rail cross-section onto the plane. This algorithm prevents the miss calculation of the shadow area, in the case of a projected vertex falling into the shadow. Finally, the cross-section was discretized with 36 vertices in each parallel face.

3.3. Finite element model

The Finite Element Model (FEM) was built utilizing the software Ansys, using the finite elements *PLANE55 and COMBIN39*. The first is suitable for 2D thermal conduction problems and is defined using four nodes, each with temperature with one degree of freedom (DOF). This element uses linear interpolation and full gauss integration. The element allows nodal loads in terms of convection or heat flux (but not both) and radiation. Since the simplified model has the three heat exchange modes concurrently, the element alone is not capable of modeling the problem. This is overcome by using the *COMBIN39* element, which is a unidirectional element with nonlinear relation between heat flow and temperature difference. It also features linear shape function and exact integration. The FEM mesh (Fig. 5) is made of a UIC54 rail profile and an arch, which includes material with high conductivity, unitary density, and low heat capacity. This material was discretized with *PLANE55* elements and was connected to the rail profile through the *COMBIN39* elements with small heat flow resistance. The arch is responsible to receive all the incoming Solar radiation and transmit it to the rail's material. After a convergence test, the mesh size was defined by 502 elements and 554 nodes.

The simulation range extends from day and time 2020/07/26 6:00 until 2020/07/28 23:55. This period was selected based on weather and rail measured temperature characteristics. The solar radiation has no cloud interruption meaning a clear sky day, as shown in Fig. 6. The convection coefficient is also shown in Fig. 6 and it was calculated based on the wind speed following Eq. 2. In addition, the air temperature exceeded 35 °C (Fig. 7).

Material properties such as specific heat and thermal conductivity are considered temperature dependents and are based on EN1993-1.2 (CEN, 2005). Constant parameters are shown in table 1. ϵ_{res} is the product of ambient and rail emissivity, 0.7 and 0.6 respectively.

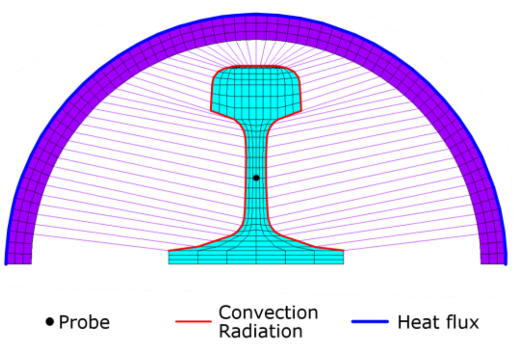

Fig. 5 | FEM mesh and loads.

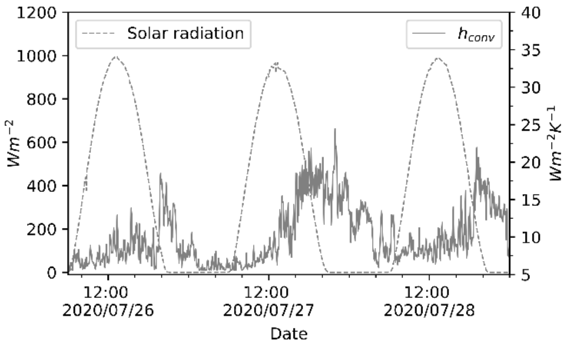

Fig. 6 | Weather-related parameters.

Table 1 | Constant parameters of the simulation.

ρ	α_s	ϵ_{res}	T_{sky}	A_c	A_r	V
$7850\ kgm^3$	0.85	0.56	T_{air}	$472.8E^{-3}m^2$	$472.8E^{-3}m^2$	$7.16E^{-3}m^3$

The total duration of the simulation is 237 300 seconds, totalizing 65.8 hours. The standard time step of the solution is set to 60 seconds and the maximum and minimum were set to 200 and 10 seconds, respectively. The thermal analysis is incremental and iterative, using heat flow criterion for convergence, with a tolerance of 0.001 and a reference value of $10\text{E}^{-6}[\text{W}]$.

4- RESULTS

The solving process of the simplified model built into the python package is in good agreement with the finite element model showing no significant difference. The results are shown in Fig. 7. It means that the python software can be used to solve the energy balance model instead of FEA, which is usually not simple.

Notably, the rail temperature during these days reached a peak value of 58 °C, meaning an offset from the ambient air temperature of 20 °C at 2020/07/27 15:50. Furthermore, the lumped thermal model considers the temperature to be constant along the cross-section, which is confirmed with the FEM given the boundary conditions. This effect is demonstrated in Fig. 8.

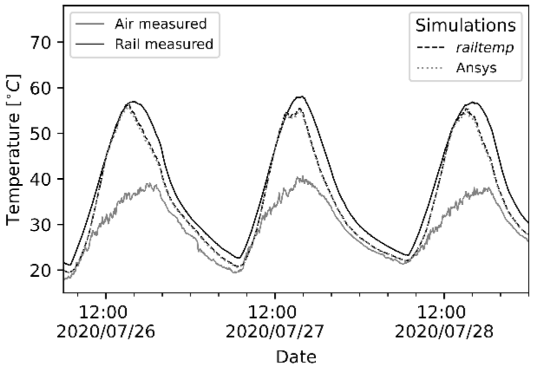

Fig. 7 | Simulations' results.

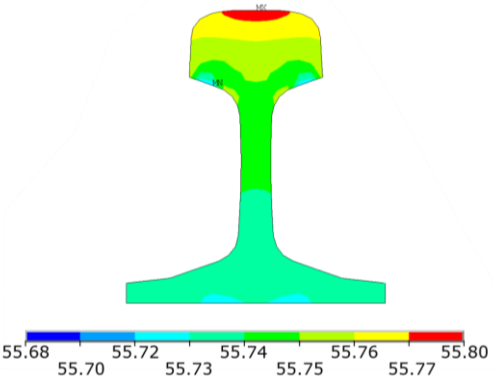

Fig. 8 | Profile results for 2020/07/26 15:15.

Comparing the simulations with the measured rail temperature, the models also show good behavior. The coefficient of determination (R^2) reached a value of 0.914 and a root mean squared error ($RMSE$) of 3.45 °C within 792 analyzed data points. However, the model has some limitations since it shows a delay when predicting the time of peak rail temperature of the day. The measured value takes place before the simulated one. Even though the value of maximum temperature shows a difference in a range of 3 °C. Taking these results into consideration the model is a good approximation and can be used to estimate and predict rail temperature if used with a weather forecast model.

5. CONCLUSION

Rail temperatures represent a great concern in the railways' safety operations. Also, it is a parameter to design and maintain the railway infrastructure, and crucial when studying buckling phenomena. Thermal models can be useful to use in these cases, especially to predict critical temperatures. The modifications of the CNU model and the adaptation to a python package are in good accordance with FEM results and validated with field-collected data. Furthermore, the developed software provides an easy-to-use, open and adaptative environment to simulate rail temperatures based on weather conditions.

The model showed a good R^2 value of 0.914 and a $RMSE$ of 3.45 °C, however it has a limitation of lagging when predicting the time instant of the daily maximum rail temperatures. There is room for improvements, mainly by deep assessing parameters with experiments, such as solar absorptivity, emissivity, and convection coefficients. Also validating the model in other locations will help to improve its performance.

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