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Development of a numerical tool for the computation of rail wheel – brake shoe thermo-mechanical interaction based on a 2D plane finite element model.

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Abstract

During tread braking operations, a friction heat flux is generated at the wheel-shoe contact interface, which can increase the wheel surface temperature. The thermal flux flowing into the wheel is not uniform, as it depends on the distribution of the contact pressure. At the same time, the remaining portion of the wheel is cooled down by natural convection, radiation and rail chill effect, i.e., the cooling due to contact with the fresh rail. Therefore, the wheel is prone to thermo-mechanical stresses and strains, which can eventually damage the wheel surface, due to shelling and spalling. Furthermore, in special conditions, a microstructural transformation of the wheel steel can occur, and brittle martensite can be generated. Hence, it is essential to predict the wheel-shoe thermal behaviour in the frame of predictive maintenance as well as to increase the braking performances of new shoe materials. The present work deals with the description and preliminary validation of a new numerical tool for the simulation of the wheel-shoe thermomechanical behaviour, which was developed with the aim to find the best compromise between a detailed modelling of the phenomenon and computational efficiency. The tool includes a Matlab routine for the solution of the equations describing the dynamics of a braked railway wheel and two plane finite element (FE) modules, implemented in ANSYS Mechanical APDL. The first FE module performs a static structural analysis to calculate the distribution of the normal and tangential pressures at the contact interface, while the second FE module performs a transient thermal analysis to compute the evolution of the wheel temperature during a braking operation. To reduce the computational needs, the mechanical and thermal problems are decoupled and only a limited portion of the wheel is modelled in the thermal module, by superimposing adiabatic boundary conditions at the lateral edges. The present paper describes the modelling strategy adopted and the implementation of the FE modules in ANSYS, also giving light to the preliminary results obtained with the new code. The code validation shows a good agreement of the calculated temperature with results available in the literature. For drag braking operations, it is shown that the 1Bg configuration is more thermally harmful with respect to the 2Bg arrangement, and that at constant braking power an increase in the running speed reduces the wheel temperature thanks to air convection.

Keywords: tread braking, cast iron brake shoes, conformal contact, finite-element method.

1 Introduction

Tread braking is the traditional braking system installed on freight vehicles, due to its simple design and ease of installation. However, the friction heat flux generated at the contact interface can heat up the wheel, and this leads to high thermal stresses and strains, which can in turn give rise to surface defects, such as hot spots, shelling, spalling, wheel warping and even induce local formation of brittle martensite [1, 2]. Therefore, the availability of models for the calculation of the wheel-shoe thermo-mechanical interaction can be a turning point in optimizing maintenance scheduling and wheel reprofiling operations, as well as in designing new braking systems and shoe materials.

Although works proposing analytical methods are witnessed in the literature [3, 4], currently the typical strategy is the development of finite element (FE) models. These models can be either 2D axisymmetric or 3D. However, 2D axisymmetric models [5-10] are not suitable for the prediction of hot spots, as they assume constant heat fluxes in circumferential direction, while 3D models [11-14] require huge computational efforts, especially when they are also demanded to solve the contact problem. At the same time, 2D plane models in the radial-circumferential plane were developed too, however they either perform an a priori assumption of the contact pressure [15, 16] or they neglect some important phenomena [17], e.g., the dependency of the convection coefficient on wheel speed and the rail chill effect.

The present paper describes a new 2D plane FE model, implemented in ANSYS Mechanical APDL, developed with the goal to achieve the best compromise between the accuracy of the description of the phenomenon, in terms of solution of the contact problem and simulation of the heat fluxes involved, and the computational efficiency. The model considers three main thermal contributions: friction heat flux, air convection and rail chill. The reduction of the computational times is obtained thanks to two main strategies. First, the mechanical and thermal problems are decoupled, so that the contact problem is solved with a dedicated FE module, performing a static analysis, and then the distribution of the normal and tangential contact pressures are fed to a thermal module, performing a transient analysis, for the calculation of the wheel temperature evolution. Moreover, the thermal module models a limited portion of the wheel, under the hypothesis that the heat flux in circumferential direction is negligible with respect to the radial direction.

2 Methods

The proposed tool for the investigation of the wheel-shoe thermo-mechanical behaviour includes three main modules, see Figure 1, namely a Matlab routine, a FE structural module and a FE thermal module. Both FE modules are implemented in the commercial ANSYS Mechanical APDL software. The tool can investigate stop and drag braking operations, 1Bg and 2Bg block configurations as well as different brake shoe materials, however the preliminary results presented in the next section only refer to drag braking operations and traditional P10 cast iron brake shoes.

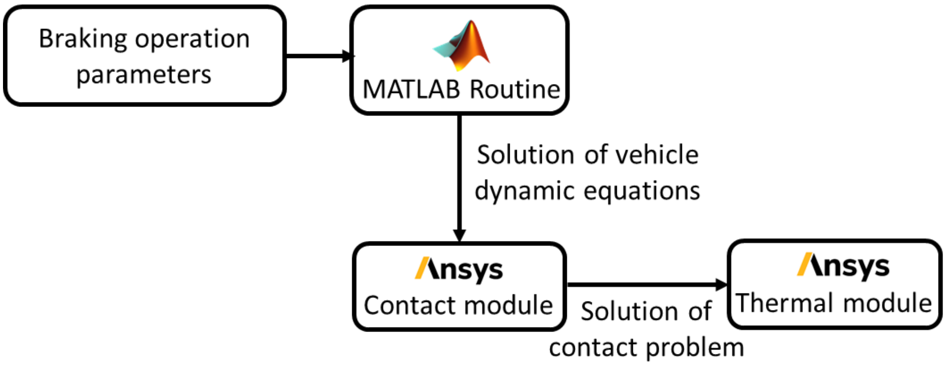

Figure 1: Flow-chart of the new tool.

The Matlab routine solves both the longitudinal train dynamics (LTD) equation and the rotational equilibrium equation for the braked wheel, based on an existing LTD code [18-21] and an existing heuristic wheel-rail adhesion model [22-25] developed in past activities. Starting from the results computed by the Matlab routine, which for drag braking operations correspond to wheel-shoe pressing force and friction coefficient, the FE contact module calculates the distribution of the normal and tangential pressure at the wheel-shoe interface, thanks to the application of ANSYS 2D surface-to-surface contact elements CONTA172 and TARGE169, solving the problem with the augmented Lagrangian method [26]. The rest of the wheel and shoe is meshed with the PLANE183 element, applying the normal force on an external node which is connected to the brake shoe with rigid elements, representing the block holder, see Figure 2a).

From the distribution of the contact pressure, the thermal module calculates the heat flux flowing into the wheel in each circumferential position. The thermal module only models the wheel, which is meshed using the PLANE77 elements. The thermal loads are applied to layers of SURF151 elements, by defining two ANSYS tables for the convective and friction heat fluxes. The nodes of the wheel outer periphery not in contact with the shoe undergo cooling due to air convection, with the convection coefficient being a function of the wheel speed [27], while the rail chill effect is applied to the nodes that would be in contact with the rail through an equivalent convection coefficient [8]. To reduce the computational efforts, only a 45° sector of the wheel is modelled, and an adiabatic boundary condition is superimposed to the lateral edges, thus assuming that the heat flux in circumferential direction has a limited effect compared to the one in radial direction, see Figure 2b).

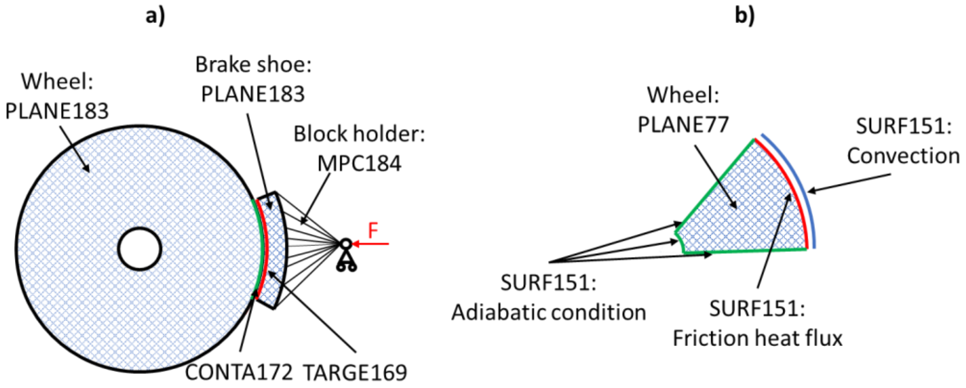

Figure 2: Mesh of a) contact module (1Bg) and b) thermal module.

3 Results

To validate the new model, a drag braking operation with conditions corresponding to the ones simulated and reproduced experimentally by Vernersson [28] (wheel speed of 100 km/h, axle-load of 20 tonnes, braking power of 31.5 kW, 1Bg cast-iron shoe arrangement) was first investigated. The new model predicts a temperature increase by 226.8 °C after 15 minutes, which is in excellent agreement with the 225 °C value calculated by Vernersson.

Then, the code was launched to compare the wheel temperature evolution obtained with 1Bg and 2Bg cast iron block arrangements under the same braking scenario suggested by the standard [29], namely a drag braking operation with track slope of the Gotthard line (21‰) and running speed of 60 km/h. Obviously, since the 2Bg configuration features two contact interfaces, the normal force acting on each wheel-shoe contact patch is lower, and the friction heat flux generated at the single wheel shoe-interface is much lower, see Figure 3a). Furthermore, a wheel node is cooled down by convection after the contact with the first shoe and as a result, the final temperature for the 2Bg configuration is lower, while focusing on a single wheel revolution, it can be observed that the difference between the maximum and minimum recorded temperature in a revolution is higher for the 1Bg arrangement, which therefore is more thermally harmful, see Figure 3b). Please note in Figure 3a) that since the contact algorithm considers the effects of friction and sliding, the heat flux distribution, which is proportional to the pressure distribution, is not symmetric, and a peak at the leading edge is observed, which is due to block jamming effects.

Finally, a simulation was also carried out at constant braking power of 31.88 kW for three different values of the running speed. The block arrangement considered in this case is the 2Bg configuration, which is less thermally stressful and therefore more common on freight vehicles. As noticeable in Figure 4, for larger running speed values, the final wheel temperature decreases as the convection heat flux is lower at lower speeds. Furthermore, when the wheel speed increases while keeping the braking power at a constant value, the pressing force decreases, and this leads to lower contact pressures and lower friction coefficients.

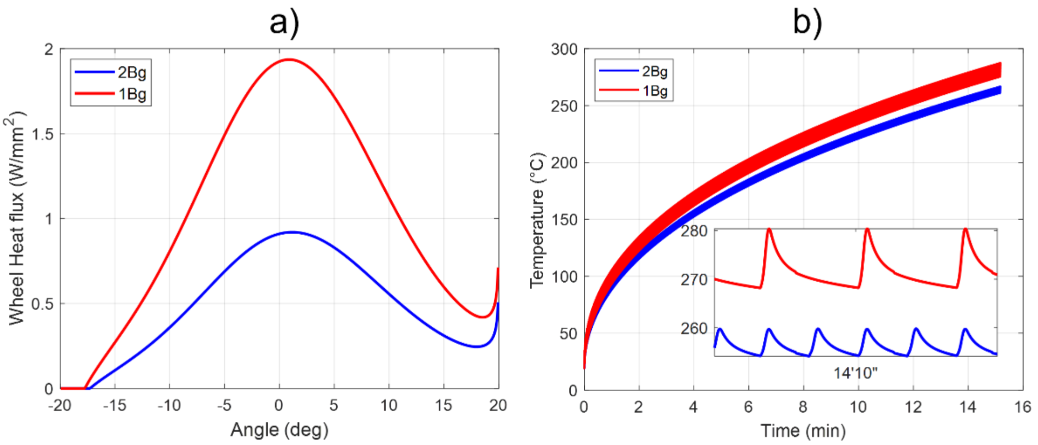

Figure 3: 1Bg and 2Bg configurations comparison. a) Heat flux and b) wheel temperature.

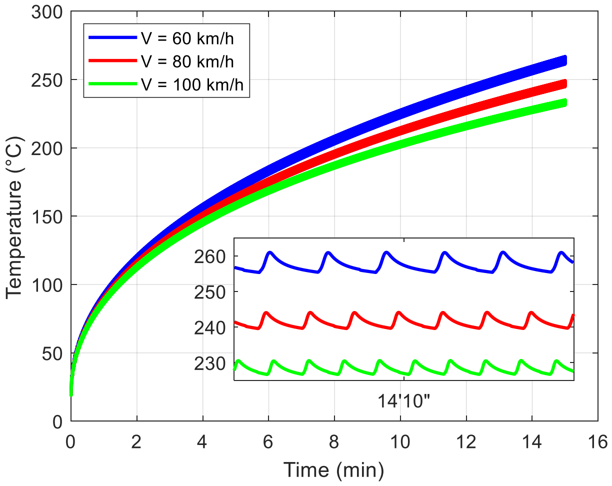

Figure 4: Wheel temperature evolution for different values of wheel speed (2Bg).

4 Conclusions and Contributions

The present work shows the development and validation of a new tool for the simulation of the wheel-shoe thermo-mechanical interaction, designed to ensure a good compromise between accuracy of output results and reduction of the computational times. The main strategies to limit the computational effort include the decoupling of the mechanical and thermal problems and the modelling of a limited portion of the wheel in the FE thermal module, thanks to the definition of ANSYS tables, which allow to reproduce the wheel rotation by rotating the thermal loads.

A simulation of a drag braking operation similar to a literature case study shows a good agreement between the wheel temperature calculated by the model and the values obtained experimentally and used for the validation of the 2D axisymmetric models developed by Swedish researchers. Therefore, the model can be considered as suitable for the simulation of the wheel-shoe thermo-mechanical behaviour in drag braking operations.

A big point of merit of the present code is the contact module, which solves the wheel-shoe contact problem considering friction and sliding. The pressure distribution is asymmetric due to friction and features a peak at the leading edge, probably related to a block jamming effect caused by full sliding. Therefore, the model can be regarded as able to study thermo-elastic instability phenomena, which occur at the contact edges.

The comparison between the 1Bg and 2Bg block arrangements under the same drag braking operation shows that, as expected, the 1Bg configuration can lead to higher surface temperatures and therefore it can cause more damages to the wheel surface.

Finally, simulations performed with the same braking power and block configuration but different wheel running speed show that the convective heat flux plays a key role in tread braking, as when the running speed increases the wheel temperature tends to be lower due to the increase of the convection coefficient.

The new tool can be easily adapted to simulate stop braking operations as well as different shoe materials, therefore future works will deal with the investigation of the effects of different composite and sintered shoe materials in both drag and stop braking operations.

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