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Direct Reconstruction of Thermal Hotspots in Tread Braking Using Explicit Finite Difference Method

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Thermal hotspots frequently arise in systems involving sliding frictional contact, induced by spatially non-uniform heat generation, leading to severe thermal gradients, localized material degradation, and surface damage. Railway tread braking provides a representative example, where infrared thermography reveals strongly localized temperature patterns that are difficult to reproduce using conventional forward thermal models. Analytical solutions are generally not suitable for capturing such transient effects, as the localized heating breaks the symmetry assumptions typically required, highlighting the need for numerical approaches. Inverse heat conduction methods enable reconstruction of unknown thermal loads from temperature measurements, but classical approaches are typically ill-posed and rely on iterative optimization and regularization procedures, resulting in high computational cost and limited robustness in transient analyses. These hotspots are critical for predicting internal thermal stresses and understanding the mechanisms of material fatigue and damage, yet their direct measurement or accurate modelling remains challenging, primarily due to their stochastic nature, which limits deterministic prediction of their evolution. This work aims to develop a direct numerical approach capable of reconstructing the unknown heat inputs responsible for experimental hotspot formation, providing insight into internal temperature distributions and enabling more accurate assessment of stress and damage within the wheel.
A 3D finite difference discretization of the heat conduction equation combined with explicit Euler time integration is employed to solve the inverse thermal problem. The explicit formulation ensures that the temperature field at each step depends only on previously known states, allowing sequential reconstruction of the unknown thermal input directly from temperature measurements in the form of thermographic data. This non-iterative approach captures strong spatial gradients associated with hotspot formation while avoiding the high computational cost and potential instability of traditional iterative inverse methods. The method also enables exact reconstruction of the imposed temperature field at the boundaries, providing a rigorous match between the modelled and imposed thermal conditions, which is critical for accurate assessment of hotspot development. Spatial and temporal discretization parameters are carefully chosen to satisfy stability conditions and maintain numerical accuracy, ensuring that localized heating patterns are faithfully reproduced. The method naturally accommodates the sharp thermal gradients observed in hotspots, which are essential for subsequent stress analysis.
Temperature measurements were acquired using a broadband MWIR camera along a single fixed axial line on the wheel tread. As the camera records at regular time intervals during the braking sequence, wheel rotation enables reconstruction of the temperature evolution across the entire tread. . These measurements were coupled with one or two sliding thermocouples used for calibration of the average emissivity, providing consistent input for the reconstruction of hotspots. The proposed approach is validated against these measurements and reference numerical solutions representative of tread braking conditions. Results demonstrate that, for the given cases, the method accurately reconstructs hotspot intensity and transient behaviour, reproducing both the spatial localization and temporal evolution observed experimentally. Detailed maps of internal temperature gradients enable more precise calculation of thermal stresses within the wheel, supporting evaluation of material fatigue and predictive maintenance. The approach also allows exploration of different experimentally studied braking scenarios and operating conditions, demonstrating robustness and scalability for parametric studies.
Overall, the study shows that explicit finite difference schemes provide a computationally efficient and physically consistent framework for inverse thermal analysis of localized heating phenomena. By directly linking thermographic measurements to numerical reconstruction, the proposed method offers an accurate and practical tool for analysing hotspot formation in tread braking and other friction-driven systems. The approach facilitates improved assessment of internal thermal stresses and supports detailed damage prediction, providing a foundation for design optimization, reliability analysis, and enhanced maintenance strategies in systems

where heat sources cannot be directly measured. The ability to reconstruct detailed temperature gradients across the tread enables a more precise evaluation of thermal stresses and their contribution to wheel damage, supporting both predictive maintenance and engineering design improvements.

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