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Virtual Simulation Modeling and Validation of Traffic Measurement Equipment Based on Multi-Physical Field Coupling

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Abstract: As the smart transportation system continues to evolve, the precise and stable operation of traffic measurement equipment directly determines the overall effectiveness of traffic data monitoring and system management. Traditional field tests are limited by specific operational scenarios, narrow coverage of driving conditions, high equipment wear and maintenance costs, and fail to meet the rigorous performance verification requirements under complex environments. This study integrates theories from mechanics, thermodynamics, and electromagnetism to establish a virtual simulation framework for traffic measurement equipment, enabling accurate replication of real-world operating conditions, conducting performance simulations, and facilitating continuous model refinement. This approach overcomes the limitations inherent in single-physical-field simulations. The outcomes provide robust digital support for equipment performance testing, structural optimization, and condition-specific calibration, thereby advancing the development and modernization of measurement systems in smart transportation applications.

Keywords: Multi-physics coupling; Traffic measurement equipment; Virtual simulation; Modeling techniques; Performance verification

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1. Introduction

The development pace of smart transportation infrastructure continues to accelerate. As core hardware for traffic data acquisition and operational status monitoring, traffic measurement equipment covers various application scenarios including vehicle speed detection, traffic flow analysis, and load measurement. The operational quality of these devices directly impacts the accuracy and stability of the entire transportation system. Operating in complex outdoor environments, traffic measurement equipment faces interactions from external factors such as mechanical vibrations, temperature fluctuations, electromagnetic interference, and airflow variations, which can lead to measurement accuracy deviations and reduced operational stability. Traditional physical testing methods are costly, time-consuming, and unable to replicate diverse complex operating conditions, resulting in significant limitations in comprehensive performance evaluation. This study employs multi-physical-field coupled virtual simulation technology to establish a standardized modeling and validation framework that accurately replicates actual equipment operation conditions, providing reliable technical support for optimizing performance and adapting to complex operational environments of traffic measurement devices.

2. Fundamental theories of transportation measurement equipment and multi-physical field coupling simulation

2.1. Core structure and working principle of traffic measurement equipment

Traffic measurement equipment comprises various components including flow statistics sensors, vehicle load measurement devices, speed detection systems, and road condition sensing modules. Each component serves specific functional purposes, with the overall architecture consisting of sensing units, data processing units, fixed support structures, and signal transmission components. The equipment utilizes built-in sensing elements to capture diverse physical signals during traffic operations; these signals are subsequently converted, filtered for noise, and processed through computational algorithms within the system to generate standardized measurement data. Continuous collection of external dynamic physical parameters, such as structural deformation, temperature variations, and electromagnetic interference, can alter the sensitivity of sensing components, leading to measurement deviations. A thorough understanding of the equipment‘s fundamental structure and signal acquisition mechanisms enables effective virtual simulation modeling, precise identification of core performance fluctuation causes, and provides robust structural and theoretical foundations for developing multi-physical field coupling models.

2.2. Core concepts and simulation characteristics of multi-physical field coupling

Multi-physics field coupling simulation transcends the analytical limitations of individual physical fields by simultaneously accounting for interactions and intrinsic relationships among mechanics, thermodynamics, electromagnetism, fluid dynamics, and other physical domains, thereby accurately reproducing the actual operational behavior of systems in complex environments. Magnetic retention relays feature intricate structures with poor component consistency and suboptimal parameter coordination, leading to increased springing cycles between the armature and core as well as between moving and stationary contacts. This exacerbates arc erosion and contact wear, and in severe cases may result in contact fusion welding, causing significant changes in static and dynamic parameters such as engagement time, engagement voltage, and contact pressure [1]. The multi-physics coupling approach enables bidirectional parameter correlation and dynamic iteration across all physical fields, realistically simulating the combined effects of temperature deformation, vibration interference, electromagnetic influences, and other factors during equipment operation, ensuring high alignment with real-world application scenarios.

2.3. Advantages of applying virtual simulation modeling technology

To meet the high reliability requirements of magnetic holding relays in railway, aerospace, and other applications, this study establishes methods for theoretical analysis of static and dynamic characteristics, develops corresponding theoretical and simulation models, and examines the patterns governing these characteristics. The digital modeling approach enables precise control of various parameters while capturing subtle deformations, signal fluctuations, and precision deviations during equipment operation, thereby providing more comprehensive performance analysis. Virtual simulation testing eliminates the need for physical equipment and specialized test materials, significantly reducing R&D costs and accelerating product iteration cycles. All data generated during simulations can be fully archived and retrospectively analyzed, offering a robust data foundation for structural improvements, algorithm optimization, and performance enhancement.

2.4. Development of a virtual simulation modeling system for multi-physical field coupling in transportation measurement equipment

2.4.1. Overall design of the simulation modeling framework

By leveraging the operational characteristics of transportation measurement equipment and the principles of multiphysics coupling simulation, a hierarchical, modular virtual simulation framework can be established. This framework encompasses multiple core components: device geometric modeling, physical field parameter configuration, coupling relationship definition, simulation computation, and data output analysis. The simulation modeling of magnetic holding relays' static and dynamic behaviors involves comprehensive analysis of electromagnetic-mechanical motion interactions. Three distinct models are developed: a 3D electromagnetic field simulation model, a rigid-flexible coupled dynamics model, and a multi-physics coupled simulation model integrating coil voltage equilibrium equations [2]. The geometric modeling layer performs digital reconstruction based on actual structural parameters to ensure high accuracy between digital models and physical devices. The physical field parameter configuration layer incorporates real-world operational conditions from transportation environments, including mechanical, thermal, and electromagnetic parameters. The coupling relationship definition layer clarifies interaction mechanisms among physical fields, while simulation computations replicate complete operational states and generate comprehensive data outputs, ultimately forming a fully integrated closed-loop digital modeling system.

2.4.2. Refined construction of the equipment's geometric model

Geometric model construction serves as the foundational step in virtual simulation modeling, where the quality of model formulation directly impacts the reliability of multiphysics simulation results. The modeling process adheres to core principles of refinement, equivalence, and operational condition adaptation, involving digital reconstruction based on the actual structural dimensions of transportation measurement equipment. Minor redundant components that have negligible effect on overall performance are eliminated, while critical functional elements such as sensors, load-bearing structures, and signal transmission pathways are retained to complete the three-dimensional digital model. Given that core equipment components exhibit heightened sensitivity to various physical fields, localized mesh refinement is employed to enhance simulation accuracy in critical areas, whereas auxiliary components with stable structures and uniform force distribution utilize conventional meshing methods, achieving a balance between simulation precision and computational efficiency. Model dimensional parameters and assembly relationships undergo repeated calibration against physical prototypes to prevent simulation artifacts caused by geometric deviations, thereby establishing a robust structural foundation for subsequent multiphysics coupled simulations.

2.4.3. Parameter setting for multi-physical field coupling and implementation of coupling mechanisms

By leveraging the outdoor operational environment of transportation measurement equipment, we identify structural mechanical fields, temperature fields, electromagnetic fields, and fluid fields as the core physical parameters for simulation, with precise boundary conditions tailored to actual operating conditions. The mechanical field replicates vibrations and impacts generated during vehicle passage as well as structural deformations caused by equipment weight; the temperature field captures temperature variations resulting from day-night cycles and seasonal changes, along with associated thermal expansion/contraction effects; complex outdoor electromagnetic environments are simulated through electromagnetic field modeling; dynamic forces from wind, rain, and airflow are modeled using fluid dynamics to represent environmental disturbances on equipment casings and sensing units accurately. A bidirectional coupling mechanism among multiple physical fields is established to define interrelationships between parameters: temperature-induced structural deformation alters mechanical states, electromagnetic fluctuations interfere with signal acquisition, and airflow-generated vibrations exacerbate structural deformation. This multidimensional integrated simulation approach faithfully reproduces real-world composite operational conditions of equipment.

3. Simulation model validation and application optimization analysis

3.1. Design of the validation scheme for the validity of the simulation model

To ensure the multi-physics coupled simulation model aligns with practical engineering applications and demonstrates reliable implementation value, this study employs a hierarchical validation approach. By comparing it with experimental data from physical equipment, the simulation model is validated across three core dimensions: structural deformation, operational accuracy, and signal stability. The simulation conditions closely replicate those of actual experiments, with all environmental parameters and operating parameters fully synchronized throughout the process. Operational data from both digital models and physical devices are collected simultaneously for cross-comparison; by analyzing variation trends, fluctuation patterns, and error ranges between the two datasets, the model's correspondence with real-world equipment performance is assessed [3]. The validation covers various extreme scenarios including high/low temperatures, intense vibrations, and high-current interference. Through repeated testing, systematic errors are mitigated, subtle deviations in model parameters and coupling mechanisms are corrected, and discrepancies between simulation and experimental data are continuously reduced, thereby significantly enhancing the model's reliability in practical engineering applications.

3.2. Analysis of simulation results and tracing of performance deviations

Multi-physics coupled simulation enables comprehensive acquisition of structural deformation, measurement accuracy, and signal transmission stability data for transportation measurement devices under complex operating conditions, allowing precise analysis of how various physical fields and their interactions influence device performance. Simulation results demonstrate that when mechanical vibrations and temperature fluctuations act simultaneously on the device, stress distributions in structural components do not follow the simple additive pattern expected under independent effects, exhibiting significant nonlinear amplification effects, details that are difficult to identify through traditional single-physics simulations. In single-physics environments, performance deviations exhibit fixed patterns and limited variability; however, multi-physics coupling further exacerbates structural deformation and measurement inaccuracies, with overall error magnitudes typically exceeding the sum of errors caused by individual physical effects. Simulation data enables precise identification of root causes of performance issues, quantifies the contributory ratios of environmental factors such as temperature spikes, high-frequency vibrations, and electromagnetic interference, and pinpoints critical weaknesses including structural vulnerabilities, inadequate sensor module compatibility, and insufficient signal immunity. Furthermore, simulation analyses allow differentiation of dominant physical field impacts across operational scenarios, providing targeted recommendations for structural and performance optimization while addressing the limitations of traditional experimental methods in accurately pinpointing root causes of performance deviations under complex conditions.

3.3. Iterative optimization of the simulation model and engineering adaptation upgrades

Based on model validation results and performance deviation traceability analysis, the multiphysics coupled simulation model enables iterative optimization. By adjusting physical field coupling parameters, mesh refinement accuracy, and boundary condition settings, the model's multi-field interaction logic is refined to enhance simulation accuracy further. The study employs adaptive mesh refinement technology to improve mesh resolution in critical sensing regions, utilizes bidirectional coupling convergence criteria to strengthen data exchange stability between temperature and mechanical fields, and introduces specialized filtering boundary conditions for high-frequency electromagnetic interference components [4]. Accounting for variations across different traffic scenarios, the model undergoes modular adaptation upgrades by adjusting corresponding physical field parameter combinations for urban roads, highways, tunnels, and other operating environments, achieving cross-scenario simulation compatibility. The optimized model accurately replicates actual operational conditions of traffic measurement devices under diverse environments, serving not only for factory performance verification but also providing technical support for structural improvements, sensor algorithm optimization, and anti-interference design enhancements.

4. Epilogue

This study addresses the limitations of traditional physical testing and single simulation approaches for traffic measurement equipment by establishing a comprehensive virtual simulation modeling and validation framework based on multi-physical field coupling theory. It systematically conducts research encompassing device geometric modeling, multi-field parameter configuration, coupling relationship establishment, and simulation verification optimization. The findings overcome issues inherent in single simulations, such as insufficient operational condition coverage and low practical accuracy, enabling accurate representation of equipment performance characteristics and trend changes under complex conditions. This provides a robust digital methodology for performance analysis and structural improvement of traffic measurement devices. Future work should focus on refining coupling algorithms and model precision, enhancing simulation scenario adaptability, and promoting widespread application of virtual simulation technology in R&D and performance evaluation processes for traffic measurement systems.

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Disclosure statement

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