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Continuous Fault Injection for Pantographs of High-Speed Trains Based on AMESim and Python

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Abstract

As the high-speed rail technology rapidly evolves, the demands for equipment safety and reliability have become more stringent. This study introduces a novel continuous fault injection methodology that integrates AMESim simulations with Python scripting, exemplified through an analysis of the pantograph model. This approach provides an innovative technical means for continuous fault injection within high-speed rail systems by automating and perpetuating fault simulations. The paper meticulously details the mechanisms of fault injection implementation and substantiates the method's efficacy and precision through case studies involving a basic model and the pneumatic system of a high-speed rail pantograph. The experimental outcomes indicate that the continuous fault injection technique sustains the simulation's continuity and guarantees the fidelity of the simulation outcomes. Additionally, this research delves into the integration of fault injection within digital twin platforms and highlights pertinent considerations for practical deployment.

Keywords: digital twin, fault injection, fault diagnosis, high-speed train, pantograph, near real-time simulation

1 Introduction

With the rapid advancement of high-speed rail technology, the requirements for the safety and reliability of high-speed rail equipment have been increasingly heightened. As a mode of transportation characterized by high speed, large capacity, and high frequency, the safety of high-speed rail directly affects the lives of passengers and the stability of society. In this context, the stability and reliability of the high-speed rail's pneumatic system have become a focal point of research. The pneumatic system, an integral component of high-speed trains, is responsible for providing the necessary compressed air to power various pneumatic devices on the train. Any malfunction in the pneumatic system can directly impact the operational safety of high-speed rail.

In the domain of fault diagnosis for high-speed rail's pneumatic systems, extensive research has been conducted by numerous scholars [1–3]. However, the development of fault diagnosis techniques has been constrained due to the limited availability of actual fault samples. To address this issue, fault injection techniques have emerged, which simulate fault conditions to obtain fault samples, thereby supporting the research and development of fault diagnosis techniques. Fault injection techniques are primarily divided into two types: physical fault injection and simulation-based fault injection. Although physical fault injection can provide real fault data, its long cycle, strong destructiveness, and high cost have limited its practical application.

Software-based fault injection techniques have been widely advocated and applied due to their low cost, high efficiency, and repeatability. For instance, Chen et al. [4] modeled the high-speed train's air brake system and typical fault models using AMESim, and used model switching and fault injection methods to simulate the system. The simulation results were compared with the fault curves provided by Zhou [5], verifying the accuracy of the results. Yang et al. [6] proposed a fault injection strategy based on signal conditioning that simulates fault scenarios such as sensors, traction converters, and motors in the traction drive system of EMUs. Chen et al. [7] established models of both normal and fault conditions for the electro-pneumatic brake system and implemented fault injection including: brake cylinder faults, train pipe faults, EP valve faults, and sensor faults through a combined simulation of AMESim and MATLAB/Simulink.

However, traditional pneumatic simulation fault injection methods often set the fault conditions before the program runs and cannot achieve the introduction of real-time parameters or integration with digital twin systems. In the field of digital twins, achieving continuous fault injection has become a technical challenge. Ding et al. [8] and colleagues established an online fault simulation platform for the braking system through a combined simulation method of AMESim and LabVIEW, providing a potential solution to this problem.

Despite the great potential of combined simulation technology in fault injection, it also has some inherent issues, such as interface compatibility problems, large development workload, and decreased computational efficiency. To overcome these issues, this paper proposes a continuous fault injection method aimed at automating fault injection for models. In the case study, this paper simulates the actual leakage of pneumatic components by presetting leak apertures in AMESim and verifies the feasibility of the method through continuous fault injection in a simple model and a high-speed rail pantograph unit pneumatic model. This method has been successfully applied to the high-speed rail digital twin platform, enabling the high-speed rail digital twin system to perform fault injection through simulation, providing strong support for the fault diagnosis and maintenance of the high-speed rail pneumatic system.

2 Method

2.1 Fault Injection Method

In Figure 1 shows the fault injection method of the script.

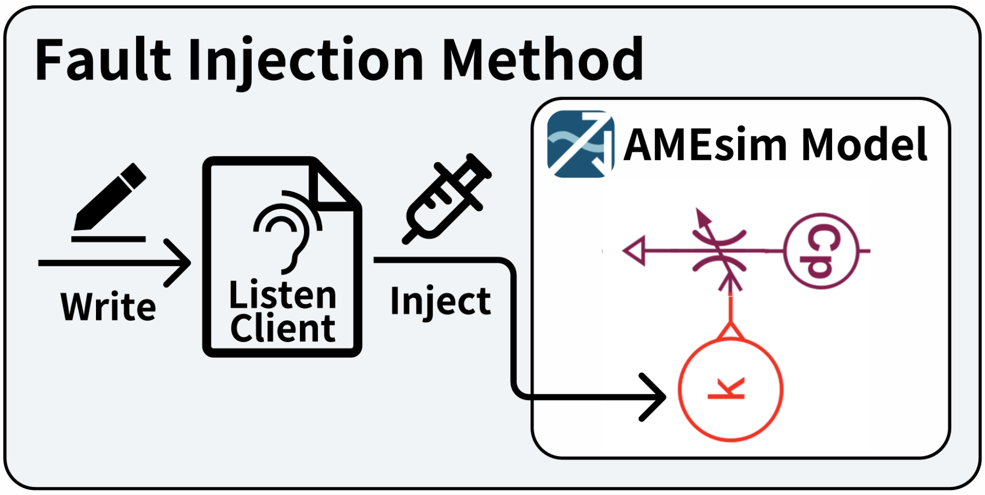


Figure 1: Fault injection method

The system simulates the leakage condition of the airbag by modifying the preset orifice area in the model through AMEsim. The corresponding model path and orifice area constant parameter are bound to a listening program. By listening to the user's input data and injecting simulation parameters, the parameter is applied at the moment of starting each segment simulation. This method of setting the orifice area in advance can effectively simulate the leakage condition of the airbag.

2.2 Continuous Simulation System

In Figure 2 shows the program flowchart of the script.

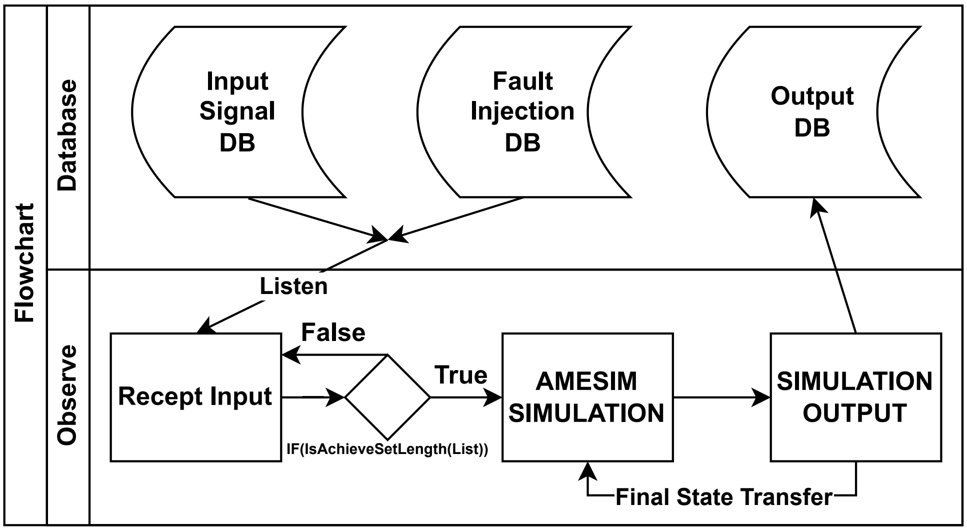


Figure 2: Program flowchart of the script

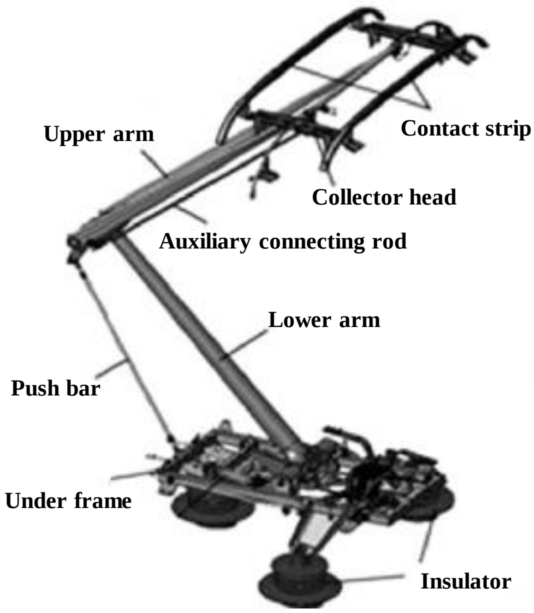
The system continuously monitors the input signal and fault injection databases, capturing data at the current moment and sequentially appending it into a list. This monitoring process is sustained throughout the software's lifecycle, ensuring uninterrupted operation. Upon reaching the specified array length, the model undergoes data loading and fault injection. Post-injection, the list is cleared, with the primary process resuming monitoring and the secondary process initiating the AMEsim simulation. Following the conclusion of the AMEsim simulation, a final state transfer method is employed to convey the simulation's ultimate state as the starting point for subsequent simulations, thus fostering a robust interconnection between simulations.

This methodology guarantees the continuity of the simulation across any temporal segment. It is crucial that the simulation duration does not exceed the monitoring duration. It can ensure that the simulation outcomes are relayed to the next simulation as initial conditions.

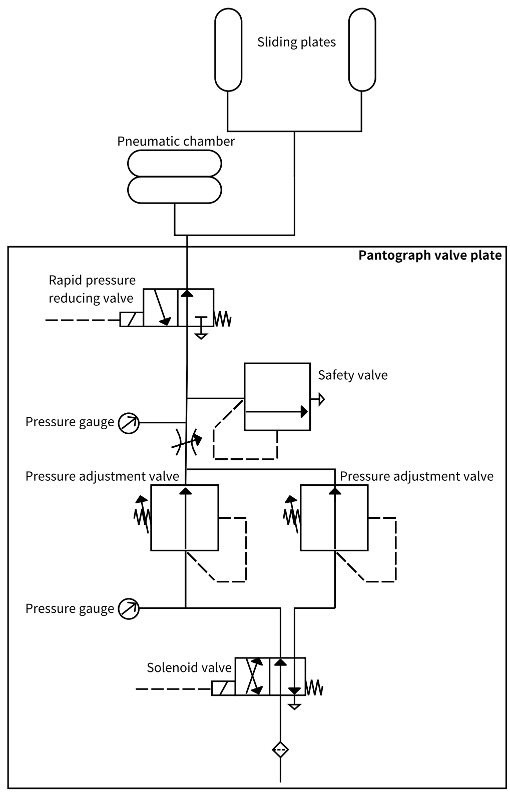
2.3 High-speed Train Pantograph

Figure 3 (a) delineates the fundamental components of a pantograph, which is a critical element in the electrical traction system of high-speed rail vehicles.

These vehicles are reliant on the transmission of electrical power from the overhead catenary system to propel their operation. The pantograph consists of several integral parts: contact strip, upper arm, auxiliary connecting rod, lower arm, push bar, and underframe.



(a) Pantograph Structure



(b) Pantograph Diagram

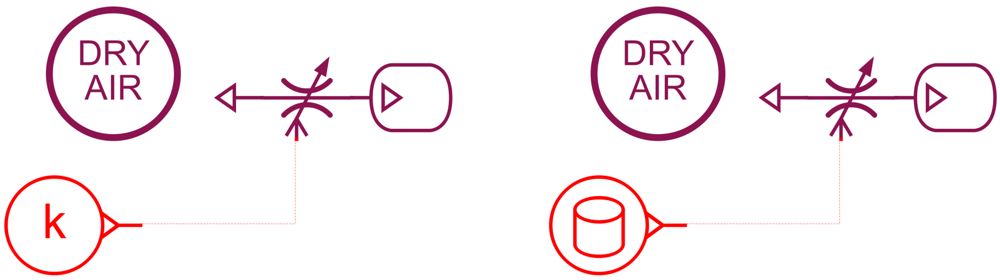
Figure 3: High-speed Train Pantograph

Figure 3 (b) illustrates the pneumatic system of a high-speed train's pantograph. The control signal is transmitted through a solenoid valve to selectively activate the pressure adjustment valve. Additionally, the rapid pressure reducing valve is actuated by the control signal to regulate the elevation of the pantograph.

3 Case Study

3.1 Simple Model

In the simple model, this paper constructed the experimental group in Figure 4 (a) to achieve continuous fault injection by controlling the constants through an external script and the control group in Figure 4 (b) to achieve fault injection through preset values. The preset pneumatic chamber pressure was 950 kPa, the set working condition was simulated for 110s, and the input orifice constants were from 0 to 1, increasing by 0.1 every 10 seconds.



(a) With continuous fault injection (b) Without continuous fault injection

Figure 4: Simple Model

In Figure 5, the experimental group (EG) achieved continuous fault injection via external script and the control group (CG) achieved fault injection through preset values. The horizontal coordinate was the simulation time and the vertical coordinate was the pressure of the pneumatic chamber.

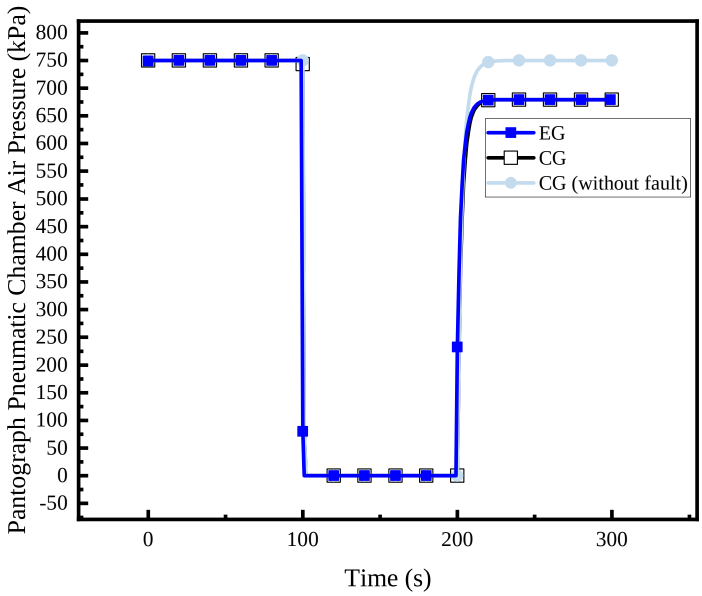


Figure 5: Simple model pneumatic chamber air pressure

The results showed that EG was basically the same as the control group, and the difference was nearly negligible.

This proved that the continuous simulation fault injection method can effectively turn the fault injection part of offline simulation into a near real-time system. This method enables the traditional offline simulation to obtain continuity while ensuring the accuracy of the simulation.

3.2 High-speed Train Pantograph Model

In Figure 6 High-speed train pantograph model, an experimental group as well as two control groups were constructed in this paper.

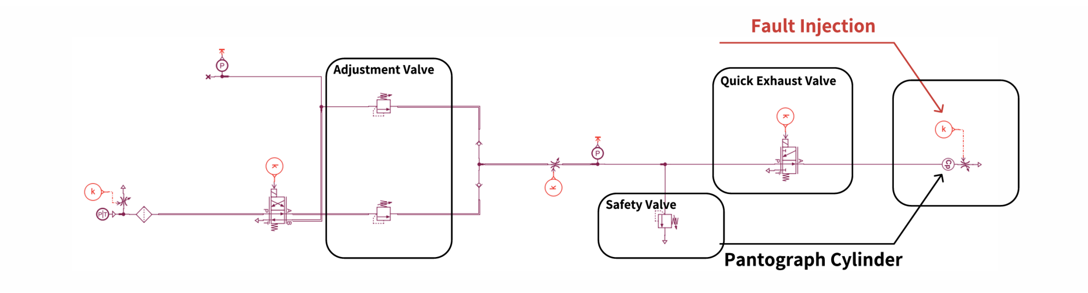


Figure 6: High-speed train pantograph model

The target pressure in this case is 750kPa, and the pneumatic chamber is inflated (or maintained at pressure) at 0-100s and 200-300s, and the air supply is disconnected and the pneumatic chamber is deflated at 100-200s. The experimental group (EG) is a continuous fault injection via an external script, and the normal control group (CG) is a fault injection via a preset value.

Both of them were subjected to fault injection, in which the constants for the orifice were increased from 0 to 0.02 in steps of 0.01 every 100 seconds. The other control group is without fault injection (CGwithout fault), where the fault injection session is cancelled.

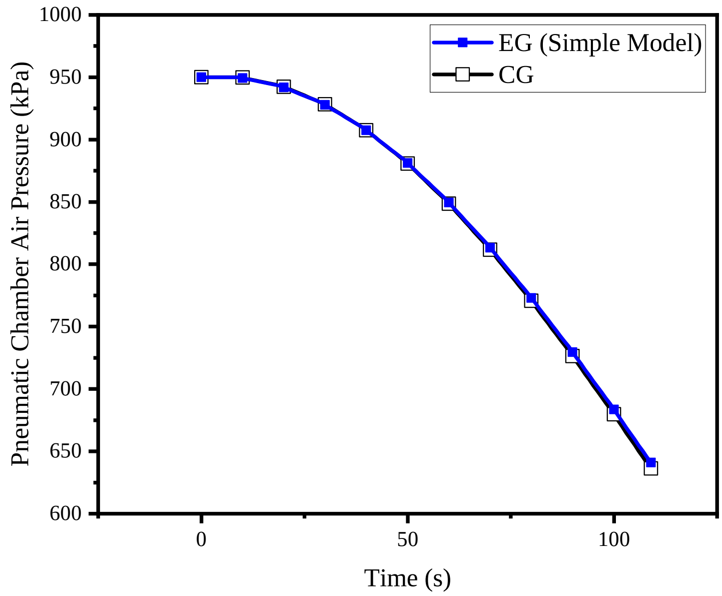


Figure 7: High-speed train pantograph pneumatic chamber air pressure

In Figure 7, the horizontal coordinate was the simulation time and the vertical coordinate was the pressure of the pneumatic chamber.

The results showed that EG and CG are basically the same, and the difference was nearly negligible. And comparing the two to the CG without fault group, it was found that the pneumatic chamber pressure produces leakage in the post-simulation process.

This proved that the continuous simulation fault injection method can effectively turn the fault injection link of offline simulation into a near real-time system in the real High-speed train digital twin. The method was validated in a real digital twin project.

4 Conclusions and Contributions

In this paper, an AMEsim-based continuous fault injection method was investigated to optimise the continuity of a digital twin system for high-speed rail airways, and an in-depth analysis was carried out with a pantograph model as a case study. With the rapid development of high-speed railway technology, the requirements for equipment safety and reliability are increasing, and fault diagnosis and performance prediction become particularly important.

The continuous fault injection method proposed in this paper provides a new technical means for real-time monitoring and fault diagnosis of high-speed railway braking system through automation and continuous fault simulation. In the method section, this paper detailed the implementation of fault injection, i.e., to simulate pneumatic chamber leakage by modifying the area of the preset orifice in the model through AMEsim, and combining with the listening procedure to achieve automated fault injection.

In addition, this paper also proposed a normal data writing method to achieve continuous data writing and fault injection by listening to the input signal database and fault injection database.

In the case study, this paper constructed a simple model and a high-speed rail brake unit air path model, and verified the effectiveness and accuracy of the continuous fault injection method by comparing the experimental group and the control group. The experimental results showed that the continuous fault injection method can maintain the continuity of the simulation while ensuring the accuracy of the simulation results, which has significant advantages over the traditional offline simulation method.

This paper also discussed the application of fault injection in digital twin platforms, which proved that the method can operate in actual high-speed railway digital twin platforms, providing technical support for real-time monitoring and fault diagnosis of high-speed railway braking systems. The promotion and application of this method is expected to further enhance the safety and reliability of the high-speed railway system, which is of great practical significance for promoting the development of high-speed railway technology.

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