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An Offline Hardware-in-the-Loop Approach to Analyse Pantograph-Catenary Interaction

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Abstract

Hybrid testing enhances the development and analysis of complex mechanical systems by integrating physical experiments with computational modelling and simulation. In the field of railway dynamics, Hardware-in-the-Loop (HiL) simulation is a prominent hybrid testing technique used to investigate the interaction between the pantograph and the catenary system. Most existing pantograph–catenary HiL setups employ a real-time numerical model of the catenary, which interfaces with a physical pantograph mounted on a full-scale test bench. However, the requirement for real-time computation imposes constraints on the numerical model complexity and size. To address these limitations, this study introduces an iterative offline HiL approach. In this method, hardware testing is guided by the convergence of results across successive iterations between testing and simulation, eliminating the need for real-time simulation. The proposed methodology is validated through experimental tests experiments, where the convergence behaviour and robustness of the approach is assessed. A discussion of the advantages and limitations of both online and offline HiL methods is also discussed, along with potential directions for future development.

Keywords: railway dynamics, pantograph-catenary, dynamic analysis, hardware-in-the-loop, hybrid testing, finite element analysis.

1 Introduction

Electric traction trains, which collect power from an overhead line, are a key aspect of railway modernisation. This system allows for cost-effective, sustainable, and fast transportation, able of covering a high transit demand of passengers and freight. A crucial component for its reliable operation relies on the pantograph-catenary interface, which ensures the collection of electric power for the train electric motors. The pantograph, mounted on the train roof, must maintain an uninterrupted and smooth sliding contact with the overhead line mounted along the track. Failures in pantograph-catenary operation can disrupt train operations and increase maintenance efforts.

Research on the dynamic coupling between railway pantographs and catenaries is an active topic of research [1]. In general, it is focused on achieving faster travel speeds, enhance compatibility between different pantograph-catenary systems, developing optimised pantographs and catenary designs, and improving maintenance and failure rate. Due to its complexity, this research is multidisciplinary, spanning across different engineering fields including simulation and experimental testing.

Despite rapid advancements, the railway industry is conservative in adopting new solutions due to stringent and costly testing requirements. Efforts are underway to replace these tests with more cost-effective and efficient alternatives, to aid the industry on deploying new technical solutions and innovative technologies.

The development and employment of dynamic analysis tools [2], able to handle pantograph-catenary dynamics, has been a key step in the reduction of expensive railway tests as well allow to better understand the dynamic behaviour of these systems. European Technical Specifications for Interoperability (TSI's) now allow the use of validated software tools to reduce the number of in line tests necessary for design type or construction assurance approval. Though the use of these tools is becoming prevalent, and the railway industry is gaining confidence on its results, these tools are still not employed to perform a complete virtual homologation. Nevertheless, they now clearly support research and development of pantograph-catenary systems.

Another pantograph-catenary dynamic analysis methodology that complements full numerical simulations is the Hardware-in-the-Loop (HiL) simulation. Here, a physical component replaces a numerical model which interacts with a virtual environment, allowing the component to be more accurately represented in a simulation environment. In general terms, typical pantograph-catenary HiL implementations consist of a pantograph mounted on a specialised test bench which is able to mimic the movement of catenary contact wire through a series of actuators. Some of these setups are able to represent the vertical movement of the wire only, while others are able to include that lateral stagger movement of the catenary contact wire. The movement of the wire is evaluated in real-time according to the contact force between the pantograph and the actuators, monitored by the test bench and fed into a catenary numerical environment [3-5]. This type of hybrid testing setups are challenging to configure, facing several obstacles that must be overcome in order that HiL framework in place is robust and accurate. One of these challenges concerns the real-time simulation of the catenary environment. This characteristic imposes limits on the complexity and size of the real-time catenary model, as well as on the ancillary control systems that govern the real-time simulation, the sensing systems on the test bench and the movement of its actuators.

To overcome the challenges related with the catenary simulation environment, this work proposes a different approach where the catenary dynamic response, and corresponding wire movement, is calculated offline. This process is setup by establishing a series of iterative runs, where the wire movement is evaluated according to the contact force time history acquired from a previous experiment, and following experimental tests reproduce the pre-calculated wire movement. The success of this approach relies on the expectation that the realized interactions are able to reach convergence. This work presents the proposed methodology and discusses initial results obtained from its application, considering a simple pantograph-catenary operation disregarding the stagger movement of the wire.

2 Methodology

The offline HiL method introduced in this work is built on the principle of avoiding real-time evaluation of the catenary model, thereby removing its limitations. To this effect, a convergent iterative hybrid testing approach is used, as depicted in Figure 1. This method also simplifies the handling of time delays due to actuator response, communication and control.

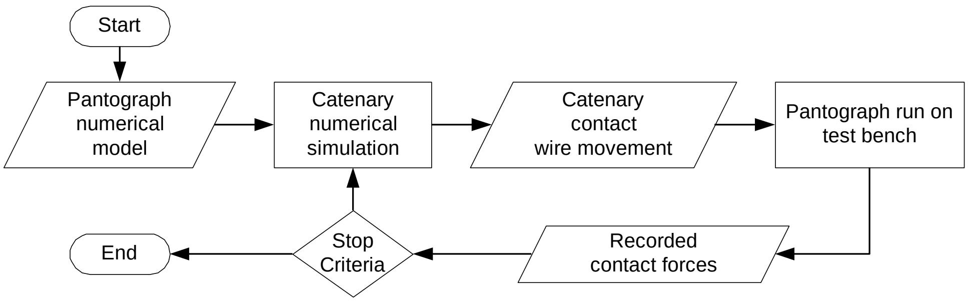

Figure 1: Offline HiL process flowchart.

In each iterative loop, the pantograph–catenary interaction is coupled by alternately evaluating the catenary contact wire movement on a dynamic analysis tool and feeding the resulting displacement setpoint data to the test bench, which will replicate the wire movement on the pantograph. The test bench records the pantograph-actuator contact forces along time, which are in turn processed and fed back to the pantograph–catenary dynamic analysis tool on the next iteration. In the first iteration, since there is still no test data to feed the dynamics analysis tool, the contact wire movement is obtained by firstly using a numerical pantograph model on the dynamic analysis tool, instead of a set of experimental contact force data. This process is run on an offline iterative loop until stopping criteria is met, assuming that a convergent state is reached. In this work the stopping criteria is set according to the difference between the standard deviation, of the evaluated contact forces, of consecutive iterations. Once this difference is below a given threshold, the offline HiL simulation is terminated.

Within the process above described, a transfer function is applied to the contact wire movement, obtained from the numerical simulation, to account and compensate for the test bench actuator response and reproduce the movement as accurately as possible. This step requires a dynamic model of the actuation stage obtained either from time-domain tests, e.g. step response, or frequency-domain trials, e.g. frequency response function. The contact force data, obtained from the physical test, is also conditioned and synchronised to establish a correct timeline between the data obtained and the simulation time.

3 Results

To demonstrate the methodology here proposed, a simple case study is defined and analysed, concerning the interaction of a pantograph travelling at 100 mph (approx. 160 km/h) with a simple periodic catenary system. In this work, the catenary system is modelled and simulated with the dynamics analysis tool, PantoCat [6,7].

The catenary model here considered is built according to Master Series design specifications (UKMS100), set for operating speeds up to 100 mph [8]. This design is currently employed in the United Kingdom on new electrification projects and line upgrades. The resulting catenary finite element model is presented in Figure 2. The model geometry is configured with 60-meter spans between supports, droppers are positioned at 5-meter intervals. The stagger is alternated at +/- 230 mm from the track centreline. For the purposes of this analysis, a region of interest has been defined between the track positions at 580 meters and 1060 meters, encompassing eight central spans.

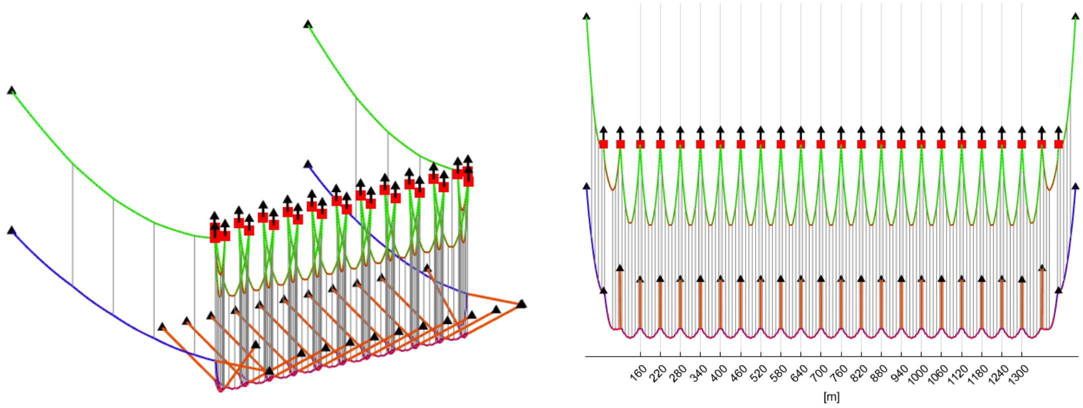

Figure 2: Representation of the catenary finite element model.

The pantograph available for this test is a Brecknell Willis HSX pantograph, which frequently operates under UKMS100 design type catenary systems in the United Kingdom. Concerning the static uplift force, this pantograph may be configured to operate under two different settings, 70N and 90N. The pantograph pneumatic pressure regulators, which control the static uplift force, have been calibrated to achieve its corresponding target uplift force according to EN50206 [9]. A previously built lumped mass model of the HSX pantograph, [10], is employed to provide an initial full numerical simulation, which in turn starts the initial offline HiL iterative process. The pantograph on the test bench is presented in Figure 3, in extended and enclosed configurations.

Figure 3: HSX Pantograph mounted on Panther test bench.

The test bench employed to follow the proposed methodology is University of Huddersfield’s Panther test bench, presented in Figure 3. This full-scale pantograph test facility has three actuation groups that interact with a pantograph, a 6 degree of freedom motion platform at the base, a two-stage vertical movement group that interacts with the pantograph contact strips and another a two-stage lateral movement group responsible to reproduce the catenary contact wire stagger. For the initial set of experiments considered in this work, the stagger movement is not considered, being only the first vertical stage actuator employed. This stage is composed by two high-speed hydraulic actuators, with a load cell at its end, which are in contact with the two pantographs contact strips. These actuators are linked to a control system set to follow the dynamic catenary contact wire height obtained from pre-processed numerical simulations. The forces on the load-cells are monitored and registered to establish the proceeding numerical simulation.

To demonstrate the convergence process of the offline HiL methodology here proposed, iterative results are here detailed concerning a test case with the pantograph static uplift force of 70N. Figure 4 illustrates the successive difference on vertical catenary contact wire displacement across all iterations. The displacement difference is presented along the simulation time in the region of interest. A clear trend is observed, where the magnitude of the initial displacements decreases progressively with each iteration, indicating convergence toward the final solution. While early displacement differences exceed 2 millimetres, they reduce to less than 0.5 millimetres in the final iterations. This consistent reduction highlights the effectiveness of the proposed methodology in achieving convergence.

A similar pattern is evident in Figure 5, which presents the iterative difference of the measured contact forces, further reinforcing the robustness of the approach.

Following EN50367 contact force evaluation procedure, [11], this difference is calculated using the contact forces filtered with a low-pass 20 Hz cut-off filter.

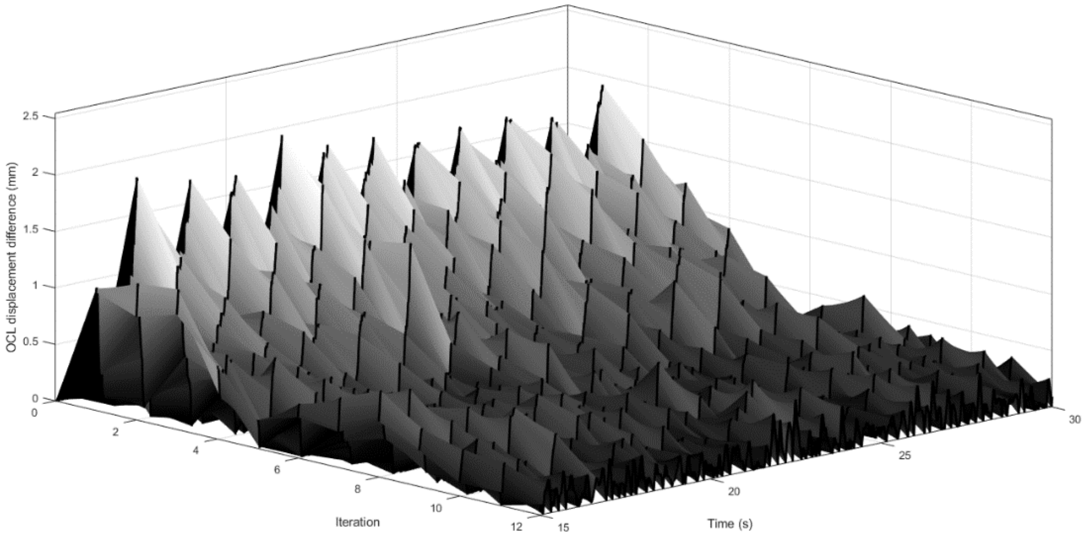

Figure 4: Contact wire vertical displacement difference between consecutive iterations.

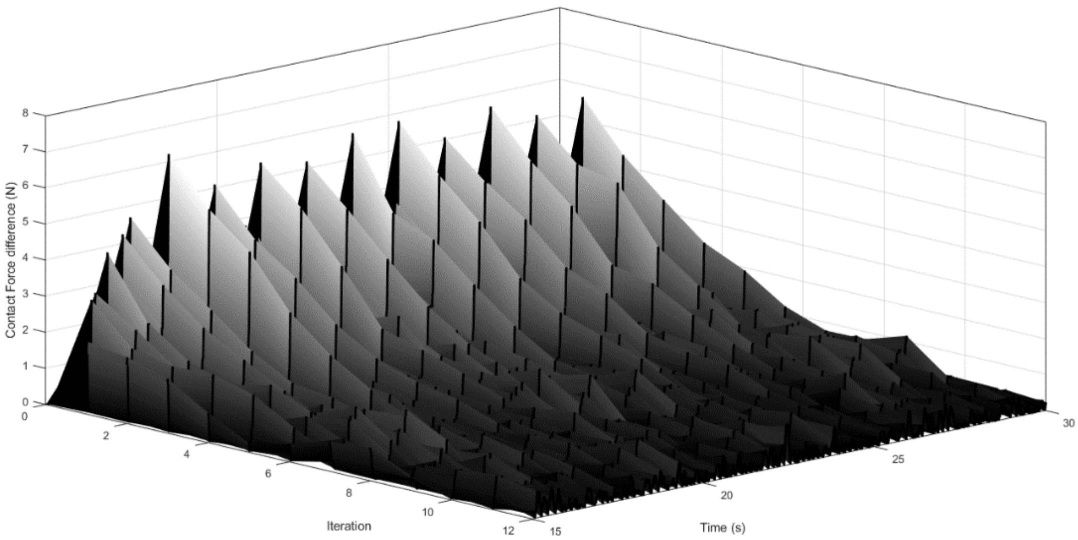

Figure 5: Contact force difference between consecutive iterations.

Figure 6 compares the contact force time history from the initial fully numerical simulation, using a pantograph lumped mass model, with the final iteration of the offline HiL test. This comparison is complemented by Table 1, which summarises key statistical parameters of the filtered contact force across each iteration of the offline HiL process. The table includes values for maximum and minimum contact forces, force amplitude, mean force, standard deviation, and the ratio between standard deviation and mean contact force. The first column, labelled Simulation, indicates the iteration cycle. The table also includes the initial fully numerical iteration, labelled *LM*. A comparison between the first and final iterations reveals that the pantograph exhibits slightly more oscillatory behaviour in the offline HiL test than predicted by the full numerical simulation. This may be due to the linear modelling approach considered when constructing the HSX pantograph numerical model. Nevertheless, the primary force patterns are already captured in the initial numerical simulation, indicating that the *LM* model provides a strong starting approximation. This behaviour is reflected in the statistical parameters of the final iteration, which show increased maximum force, amplitude, standard deviation, and a higher standard contact force std.deviation/mean ratio, along with a lower minimum contact force. In the simulations and tests performed, no contact losses were detected.

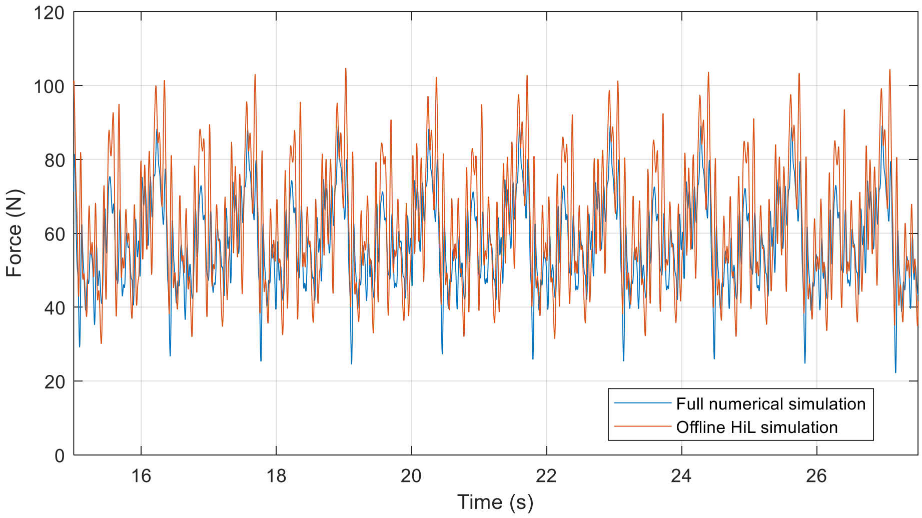

Figure 6: Comparison between contact forces obtained from of numerical analysis with lumped mass pantograph model and offline HiL simulation result.

Simulation	Contact Force [N]					σ/F_m
	F_{max}	F_{min}	Amp	F_m	σ	
LM	100.38	38.96	61.41	64.96	11.95	0.18
It 0	98.05	36.79	61.26	64.69	12.98	0.20
It 1	98.11	35.23	62.88	64.70	13.32	0.21
It 2	99.40	34.73	64.67	64.63	13.38	0.21
It 3	100.03	35.26	64.77	64.61	13.75	0.21
It 4	100.37	34.82	65.55	64.40	13.80	0.21
It 5	101.86	33.11	68.75	64.20	14.03	0.22
It 6	103.30	32.92	70.38	64.09	14.17	0.22
It 7	104.94	32.49	72.45	64.13	14.30	0.22
It 8	105.17	33.41	71.76	64.18	14.27	0.22
It 9	105.06	32.51	72.56	64.04	14.41	0.23
It 10	104.57	32.20	72.37	64.01	14.27	0.22
It 11	104.45	32.08	72.37	64.13	14.38	0.22
It 12	104.37	31.48	72.89	63.96	14.35	0.22

Table 1: Comparison of the statistical parameters of the contact force for each offline HiL iteration.

4 Conclusions

In the work, a pantograph-catenary offline HiL methodology is proposed, with the main aim to avoid real-time computation of the catenary dynamic response and corresponding wire movement. This allows in the future for larger and more complex catenary models to be able to be considered, where on an online HiL approach this would impose constrains in the model.

The methodology is detailed and demonstrated considering a simple pantograph-catenary operational case scenario. The results indicate the proposed procedure has a good level of robustness and is able to achieve a convergency state. Once this initial study in now established, future developments will introduce more complexity to the catenary system. This includes the consideration of the lateral stagger, overbridges and level crossings and overhead line systems set in curved track. Discrete features such as neutral sections and section insulators may also be included in the future. Another point for future research is on considering the start of the iteration process without a previous simulation with a pantograph numerical model, considering no previous knowledge of the pantograph to be tested. This may be achieved by only considering a constant force at the start of the iteration, with additional iterations possibly being required.

In comparison with a real-time HiL approach, the offline mode is able to consider higher a complexity of the virtual environment at the cost of a more time-consuming iterative process, where the initial conditions at the start of each test iteration need to be carefully controlled. Another practical benefit is that any previous catenary models, developed on a classic pantograph-catenary dynamic analyses software, can be directly employed on the offline iterative process. This avoids the need for the model to be re-modelled or re-processed so that is able to run in a real-time.

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