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Modelling of pantograph-catenary interaction around critical speed

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Abstract

The dynamic interaction of pantograph and catenary in electrified railway systems has considerable research attention, both in terms of simulation and of measurements. The simulation benchmark of 2015 proved a good base of agreement between established models, but also showed that deviations between the different models increase when the simulated system approaches critical speeds. From these deviations it can be concluded that some of the models in the benchmark better depict the system behaviour around critical speed than others. Therefore, this paper analyses and compares measurement data from the Green Train project in Sweden, which includes speed at and over critical level, to simulations performed with one of the participating models, the finite element (FE) based CaPaSIM model. Based on this comparison, modelling alternatives are implemented and tested in CaPaSIM, to examine if they improve the accuracy of the model in the speed range around critical speeds. These alternative modelling approaches are to a large extent based on previous studies in the field, such as other models that participated in the benchmark. The varied aspects include choice of element type for single components of the catenary and element mesh resolution. On the pantograph side, the effect of separately modelling independent flexible collector strips is studied. The modelling choices that prove to be most promising during the initial variation tests are presented and recommendations are given for further investigations of possible improvements.

Keywords: pantograph-catenary dynamics, critical speed, finite element modelling, electric railways.

1 Introduction

For reliable operation of high-speed railways, large volumes of simulations and measurements on the dynamic interaction between pantograph and catenary are performed during the development and approval process [1]. An example is the Green Train project study for a new high-speed train in Sweden from 2005 to 2011. For this study, simulation and testing of the dynamic pantograph-catenary interaction were performed at the design limits of the available systems [2]. During one test run with a speed profile exceeding the critical speed of the catenary, the pantograph dynamics were measured.

In the dynamic pantograph-catenary interaction, the critical speed is an important design metric that is defined at 70 % of the wave propagation speed. Exceeding this speed in operation leads to excessive dynamic amplification factors in the interaction and should therefore be avoided [1]. For the mentioned measurement run, the train reached a speed of up to 84 % of the wave propagation speed. In preparation of the measurement run, simulations were performed to ensure the safe system behaviour. These simulations were run in the CaPaSIM FE-model [3], which was developed by Trafikverket and KTH. However, the simulations overestimated the dynamic amplification of the contact force between pantograph and contact wire. Above critical speed, the measured standard deviation σ of the contact force are considerably lower than those obtained from the simulation. This is especially pronounced in the 5–20 Hz frequency band.

In the simulation benchmark for dynamic pantograph-catenary interaction presented in 2015 [4], the results indicated a similar pattern. For the final simulated speed step of 365 km/h, which is 80 % of the wave propagation speed, there are pronounced disagreements for the extreme values of the contact force as well as the contact force rms in the 5–20 Hz frequency band between the different simulation models. This indicates that there might be simulation approaches among the other models that can capture the observed phenomenon. Based on these different simulation approaches, this study aims to identify the effect of different modelling choices on observed deviations. The previous studies range from other models that participated in the benchmark [5]–[8] to later studies focusing on increased accuracy at high speeds [9] or the consideration of variations in the system [10], [11]. This paper fist states the modelling approach and changes made. It then presents the observed improvements and gives recommendation for further work in this direction.

2 Methods

For the measurement performed in 2007, an experimental pantograph was mounted on the test vehicle and run at speeds up to 306 km/h. The data contains contact forces for each collector strip. From this dataset, four time-segments with approximately constant speed are extracted and analysed (see Figure 1). The aerodynamic uplift coefficient used in the simulation is determined by curve fitting from the measurement data. After low pass filtering at 20 Hz, the standard deviation σ of the contact force is extracted.

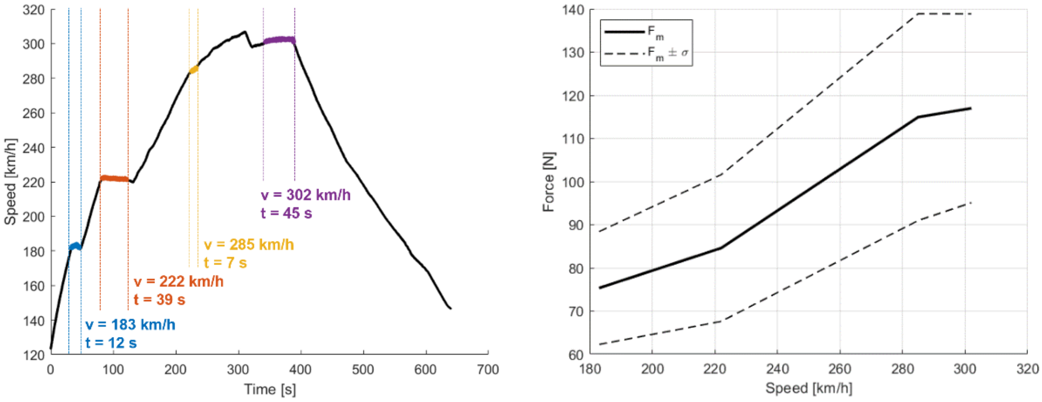

Figure 1: Speed profile of the measurement run with four extracted sections (left) and the resulting statistics of the contact force (right).

The setup of the original CaPaSIM model is described in [3]. For this study one entire catenary section of SYT7.0/9.8 as present during the measurements, is modelled in 3D with FEM as specified in Figure 2 and Table 1. The original setup of the FE-model has 4-8 beam elements between two droppers, but more recent studies tend to use a higher mesh resolution [9]. For studies on the critical speed, it must avoid a large influence of numerical phenomena on the simulation results, which is ensured by mesh convergence. The original set of element types used in CaPaSIM are as listed in Table 1. The impact of exchanging contact wire and messenger wire elements with Timoshenko beam and Euler-Bernoulli beam elements, respectively, is studied.

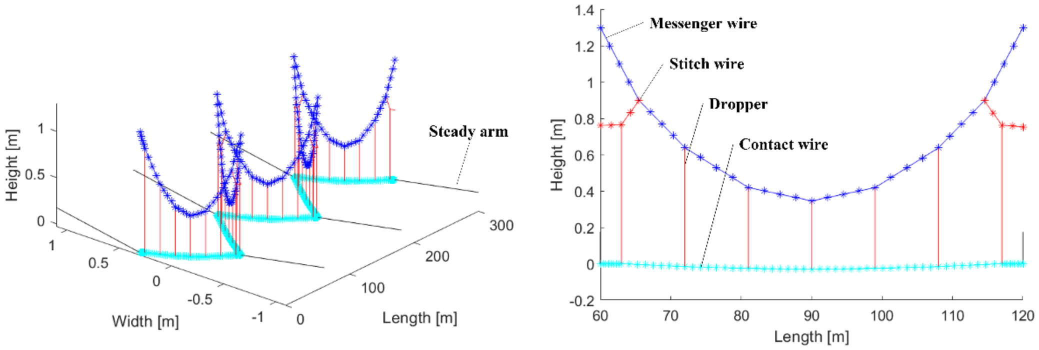

Figure 2: 3D view of the structural FE mesh of the catenary (left) and detailed view of one catenary span (right).

	Contact wire	Messenger wire	Stitch wire	Dropper
Tension [kN]	9.8	7	1.6	
Mass per unit length [kg/m]	0.89	0.45	0.31	0.11
Element type	Euler-Bernoulli	Link	Link	Tension-only link
Span length	60 m			
Dropper distance	9 m			

Table 1: Characteristics of the modelled catenary system and FE-model.

The original CaPaSIM pantograph model is shown in Figure 3. Measurement data for the two collector strips is individually available, an important refinement step is to also represent these separately in the model. In addition to adapting model parameters as in [10], the aerodynamic uplift force is adapted to depict the imbalance between the two collector strips [12]. The resulting uplift coefficients for each collector strip that are used for the simulations are shown in Figure 3.

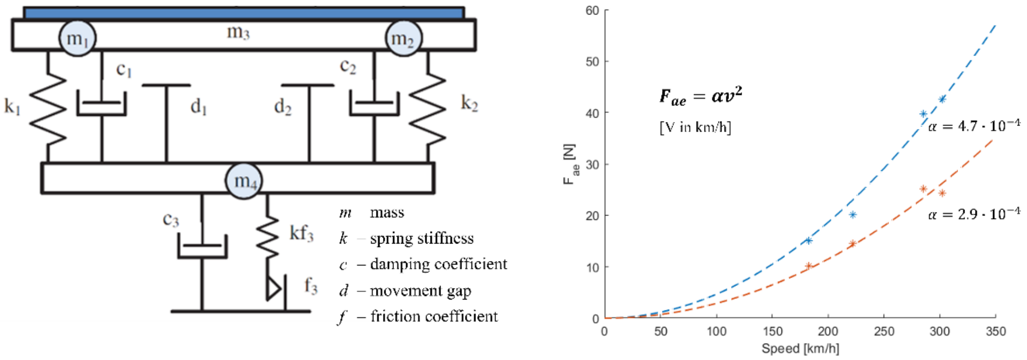

Figure 3: Pantograph model suspension setup [13] (left) and the fitted aerodynamic uplift coefficient for the two collector strips (right).

3 Results

The data sections for 222 and 302 km/h are studied more in detail. Due to simplifications, the entire frequency spectra of simulation and measurement results are not closely compared. Instead, the focus lies on noticeable deviations in the main resonance frequencies and their correlation to the statistical deviations. Figure 4 shows that the frequency band of 5-20 Hz contains the most severe overestimations of contact force amplitude. The frequencies around dropper passing frequency are sticking out, especially for the case over critical speed.

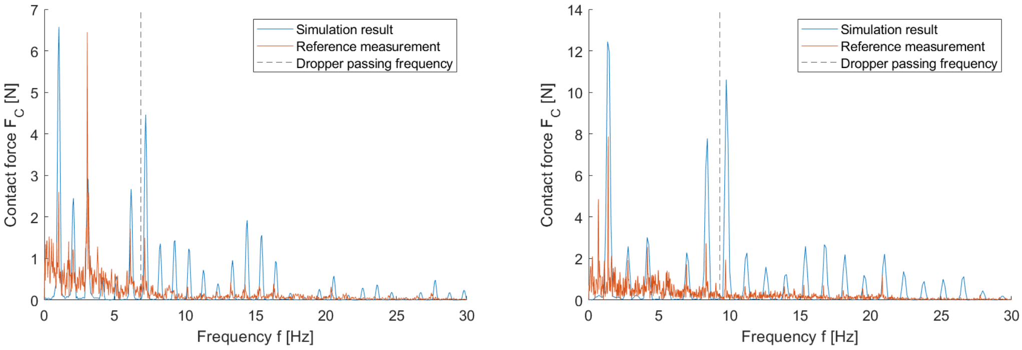

Figure 4: Frequency spectra for the simulated contact forces and the corresponding measurement at 222 km/h (left) and 302 km/h (right).

The study of mesh convergence for the contact wire is here based on the standard deviation σ of the contact force F_c after low pass filtering at 20 Hz. The values in Table 2 show that refining the mesh by a factor of 2 to 3 compared to the original model reduces the error at 302 km/h by 8-10 %, whereas further refinement only gives marginal improvements for a large increase in computational effort.

Contact wire mesh refinement factor	$\boldsymbol{F_{c,mean}}$ [N]	$\boldsymbol{\sigma}$ [N]	$\boldsymbol{\Delta\sigma}$ [N]
1	117.66	33.30	11.42
2	117.50	32.49	10.61
3	117.47	32.40	10.52
4	117.46	32.38	10.49
6	117.45	32.35	10.47

Table 2: Statistical results of element mesh refinements for a simulated speed of 302 km/h.

The statistical results of changing the FE element types are summarised in Table 3. They show that the use of more advanced element types can improve the simulations' results to some extent. Stability issues for more large-scale changes indicate that a simultaneous refinement of the mesh is advisable in the range suggested above.

Contact wire	Messenger wire	$\boldsymbol{F_{c,mean}}$ [N]	$\boldsymbol{\sigma}$ [N]	$\boldsymbol{\Delta\sigma}$ [N]
Euler-Bernoulli	Link	118.60	35.59	13.70
Euler-Bernoulli	Euler-Bernoulli	118.67	35.55	13.66
Timoshenko	Link	118.80	34.85	12.97

Table 3: Statistical results of element type variations for a simulated speed of 302 km/h.

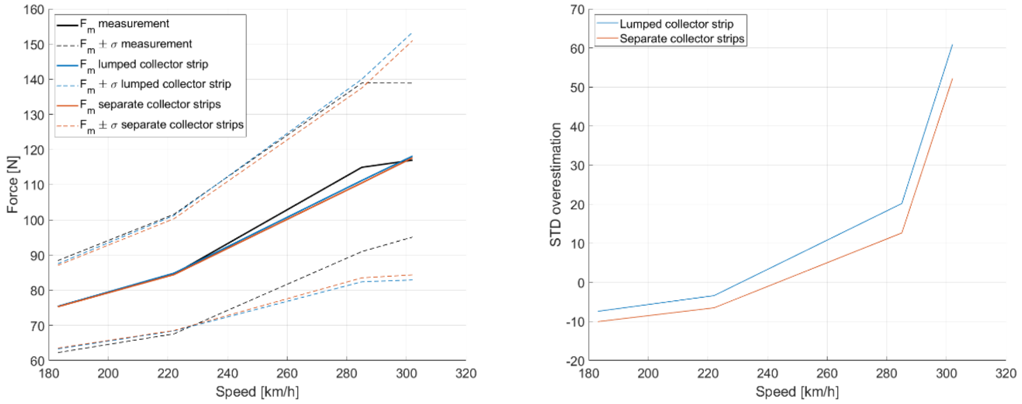

Figure 5: Resulting statistics of the contact force one and two collectors respectively (left) and comparison of σ errors (right).

As shown in Figure 5, an error reduction in standard deviation by 14 % is achieved by separately modelling the collector strips. It can also be noticed that all reductions in standard deviation are somewhat proportional to the original value.

4 Conclusions and Contributions

The variation of simulation results that was obtained already by testing a first set of modelling alternatives confirms the initial assumption that some of them have advantageous characteristics for modelling the system interaction at critical speeds, even though all of them perform similarly well at moderate speeds. For more accurately depicting the dynamic behaviour around critical speeds, the following improvements have been identified within the CaPaSIM model:

- Modelling of independent collector strips with individual aerodynamic uplift coefficients
- Increasing the contact wire finite element mesh resolution
- Using Timoshenko beam elements for the contact wire

It was shown that the improvements above lead to a noticeable, but not yet sufficient reduction of the errors compared to the original CaPaSIM model. There are still considerable deviations present in the simulation results, especially in the 5-20 Hz frequency band. Therefore, further studies are suggested that take a more comprehensive approach of mesh refinement combined with the use of more advanced element types. In further analysis of the measurement data, the pattern of force increase should be explained, also considering the reliability of the other extracted sections and possible effects of external factors on the measurement. Another focus of continued work is refining the pantograph model to consequently feature more details in behaviour that are related to individually suspended collector strips.

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