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Influence of Support Height Assembly Errors on the Pantograph-OCR Contact Force

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Abstract

In this work, the influence of assembly errors on the pantograph–rigid catenary interaction is explored. First, a finite element model of a rigid catenary is proposed, consisting mainly of beam elements and point stiffnesses to represent the supports. A straight catenary section is considered, whose nominal geometry is characterised by uniformly spaced supports mounted at the same height. Several simulations are then performed in which the supports are mounted at different heights, simulating installation errors. As a result, the probability density function of key indicators, such as the maximum, minimum, and standard deviation of the contact force, is obtained for different magnitudes of the maximum installation error allowed. All these indicators show a deterioration compared to their values in the nominal case. This work enables the determination of an assembly-error tolerance range within which the contact quality remains within acceptable limits.

Keywords: overhead conductor rail, rigid catenary, dynamic interaction, assembly errors, pantograph, contact force

1 Introduction

The overhead catenary is the structure that serves as a power supply for electrified railways. The catenary is usually classified into flexible and rigid catenaries. Flexible catenaries are mostly used in open-air railways and consist of a contact wire, a messenger wire, and several droppers. Poles and brackets serve as the structural pillars that hold these wires in the necessary position for adequate contact between the contact wire and the pantograph, the system of the railway locomotive that collects and distributes the electric energy. On the other hand, the rigid catenary is used mostly in urban metro systems due to its significant advantages in tunnels, as it requires minimal clearance for installation, is generally easier to set up, and is a low-maintenance solution.

The rigid catenary has a generally simpler structure, which consists of a contact wire fitted into a rigid aluminium profile called the overhead contact rail (OCR), and vertical supports that are directly connected to the tunnel's ceiling, as shown in Figure 1. In general, a rigid catenary installation is composed of sections that overlap at their ends to provide a smooth transition between them. Each section, whose length can range from 60 to 400 m, consists of a sequence of segments joined by inner bolted joints called flanges. The conductor rail is installed in a zig-zag shape with respect to the central axis of the track to prevent uneven wear on the contact strips of the pantograph.

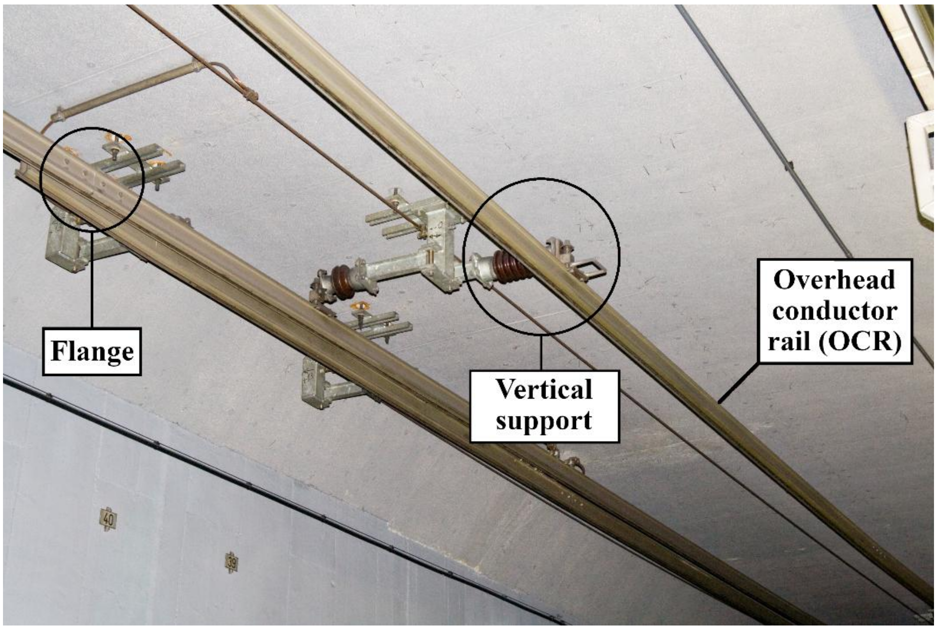

Figure 1: Main components of an OCR [1].

One of the main drawbacks of a rigid catenary is its high stiffness, which directly translates to a poor contact performance between the pantograph and the rigid catenary, especially at medium speeds and above. The contact force between the pantograph and the rigid catenary exhibits fluctuations that, on the one hand, cause wear in both the pantograph's contact strips and the contact wire, and on the other, may lead to contact losses with their associated interruption of the power supply and the appearance of arcing. The difficulty of maintaining an adequate range in the pantograph-rigid catenary contact force is one of the main reasons why maximum speed is limited in these overhead systems compared to flexible ones.

Research has been conducted recently aimed at mitigating these drawbacks and exploiting the advantages of the rigid catenary. To this end, several models have been proposed, like that of Bautista et al. [2]. Pantographs are typically modelled as lumped-mass systems while the overhead conductor rail is usually modelled by the finite element method. Vera et al. [3] proposed a full three-dimensional modelling of the cross-section although the most common approach is based on using Euler-Bernoulli [2, 4] or Timoshenko beam elements [5].

Simarro et al. [6] performed multiple simulations of the dynamic interaction between several pantograph models and two different rigid catenary systems and proved that uneven span lengths could greatly increase the fluctuations in contact force at speeds higher than 100 km/h. Feng et al. [7] analysed different OCR profiles with large moments of inertia and concluded that certain geometries could reduce contact force standard deviation by around 30% compared to a conventional conductor rail at speeds of 160 km/h and above. Wang et al. [8] also studied the pantograph–OCR interaction in a double pantograph operation, and also included the influence of wind forces in the tunnel induced by the train's own speed, which was proven to increase contact force fluctuations. Yang et al. [9] explored the causes of uneven contact wire wear and performed a tribological analysis, finding multiple causes for the even catenary damage, including the copper content of the contact wire and the magnitude of the electrical current used to power the train. Guo [10] analysed the influence of span lengths on the contact force's fluctuation and proposed optimal span lengths depending on the train's expected speed.

This work analyses the effects of support height installation errors on the pantograph–OCR interaction. Without loss of generality, a two-dimensional model is used. The initial configurations of 10 000 rigid catenaries are generated, allowing for installation errors introduced as normally distributed height offsets at each support. A dynamic simulation is then performed on each catenary model with a constant pantograph velocity. From each simulation, contact quality indicators such as the maximum, minimum, and standard deviation of the contact force are collected. This process is repeated for three different values of maximum height offset allowed, yielding a distinct probability density function of the key indicators for each case.

This study allows for the establishment of a maximum installation tolerance for support height, ensuring that the interaction with the pantograph results in proper current collection without the risk of contact loss.

2 Methods

This section first details the pantograph and OCR models, as well as the necessary parameters to carry out the simulations. Then, the different case studies are presented, in which thousands of dynamic simulations are performed using OCR models that incorporate support height installation errors, defined as normally distributed variables with different levels of dispersion.

2.1 Simulation parameters

The pantograph is modelled as a lumped three-mass model as pictured in Figure 2. This model is commonly accepted for frequencies below 20 Hz as stated in EN50318 [11]. The chosen pantograph parameters stem from a Faiveley CX pantograph whose masses, damping coefficients and stiffnesses are given in Figure 2 [6].

	m (kg)	c (Ns/m)	k (N/m)
1	8.5	6045	10
2	4.63	5400	5
3	4.8	1	32

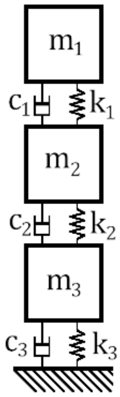

Figure 2: Parameters defining the lumped-mass pantograph model.

The OCR is represented by a finite element model with three different components: the overhead rail, the supports holding the rail, and the flanges that bind every segment of the rail. A given OCR section is defined by its number of supports, length between supports, stiffness of each support, distance between a support and a flange, as well as the nominal coordinates of each support, including height and stagger. In this work, to show the proposed methodology, an idealized OCR section with equally spaced supports and flanges.

The catenary rail, which consists of an aluminium profile and a copper contact wire, is modelled by using 2-node beam elements based on Timoshenko's formulation with an element length of 0.2 m, considering equivalent mechanical properties [6]. Each support is modelled as a point vertical stiffness. Flanges are included as point mass elements with rotary inertia. The parameters defining the OCR model can be seen in Table 1 [6].

		Value	Units
General	Number of supports	50	
	Span length	8	m
	Distance between support and flange	2	m
Overhead rail	Equivalent cross-sectional area	2.365×10^{-3}	m^2
	Equivalent density	3012.7	kg/m^3
	Equivalent Young Modulus	6.9×10^{10}	Pa
	Equivalent second moment of area	4.2468×10^{-6}	m^4
Flange	Mass	3	kg
	Rotary inertia	2.35×10^{-3}	kg m^2
Support	Vertical stiffness	400×10^3	N/m

Table 1: Input parameters defining the OCR finite element model.

In addition to the previously specified parameters, the first and the last three spans of the OCR have lengths of 1 m, 3 m and 5 m, respectively, and no added flanges. In the nominal case, all supports except those at the ends of the section are placed at the nominal height of 5.2 m over the track's plane. The section extremes are located at a fixed offset of 0.02 m above the nominal height of the rest of the supports.

Dynamic simulations are carried out with a constant velocity of 130 km/h. An uplift force of 105 N is applied to the bottom mass of the pantograph model. A penalty stiffness of 50000 N/m is included to model the interaction between the pantograph and conductor rail.

Before each dynamic simulation, the static equilibrium configuration of the OCR model is computed. Then, the simulation starts and the uplift force applied to the pantograph increases linearly from 0 N to 105 N to introduce a smooth contact initialisation. Finally, the interaction force is extracted from a central section of 25 spans, equivalent to 200 m of catenary. As an example, Figure 3 shows the contact force in the nominal case, in which every support is located evenly at 5.2 m in height with no assembly errors considered.

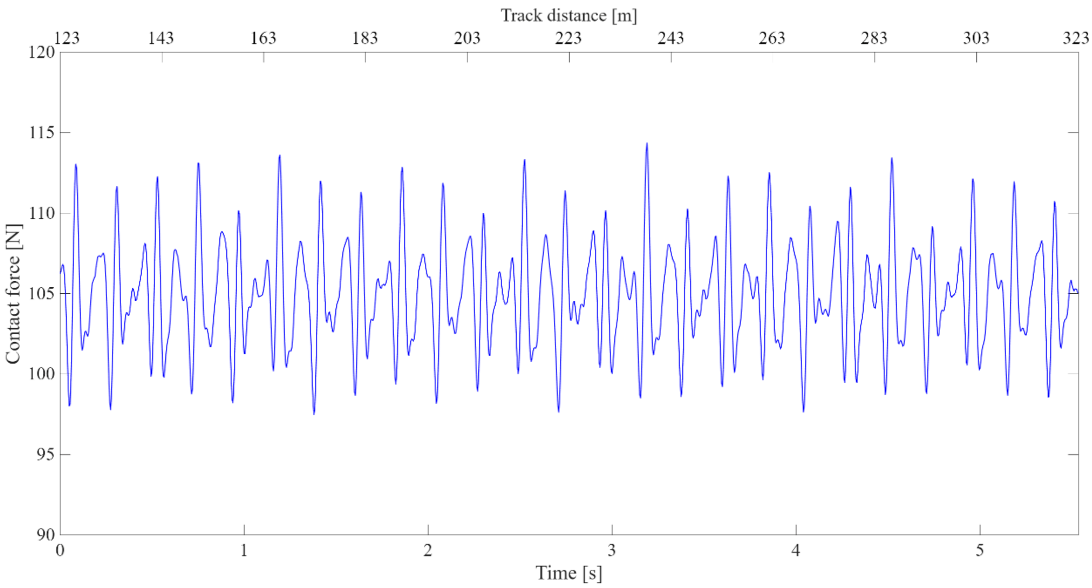

Figure 3: Contact force of the nominal case.

2.2 Case studies

Once the nominal case has been established, every support not located on the extremes of the OCR section is then added a height offset, meant to simulate installation errors, in which every support is fixed at a height different than the nominal. These offsets are set randomly by a normal distribution whose probability density follows the Gaussian function with 0 mean and standard deviation σ, as defined in Equation (1):

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{1}$$

Four case studies are considered: the nominal case, and installation errors with $\sigma = 1$ mm, $\sigma = 3.5$ mm, and $\sigma = 10$ mm. 10000 simulations are performed for each of the four cases to generate a statistically relevant data sample. Figure 4 shows an example of the randomly generated catenary model for each case. An example for each case study is shown in Figure 4, which contains a lateral view of the static equilibrium position of each randomly generated OCR.

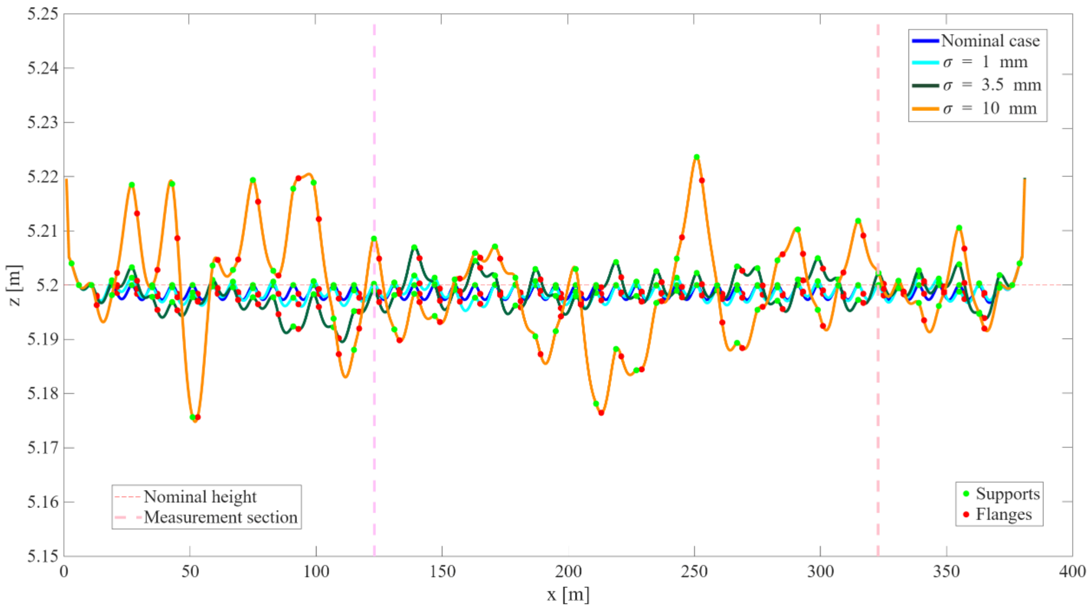

Figure 4: Catenary model case study examples

3 Results

The results are focused on the contact force maximum, minimum and standard deviation obtained from each simulation, which are key parameters regarding current collection quality.

Figure 5 shows the histograms of the maximum contact force obtained from the catenaries with installation errors defined by $\sigma = 1$ mm, $\sigma = 3.5$ mm, and $\sigma = 10$ mm. Each histogram contains the results of the 10000 simulated OCR with the same value of σ. Figure 6 and Figure 7 do the same for the minimum and standard deviation of the contact force, respectively. All results are compared to the nominal case, marked with a dashed red line in all figures.

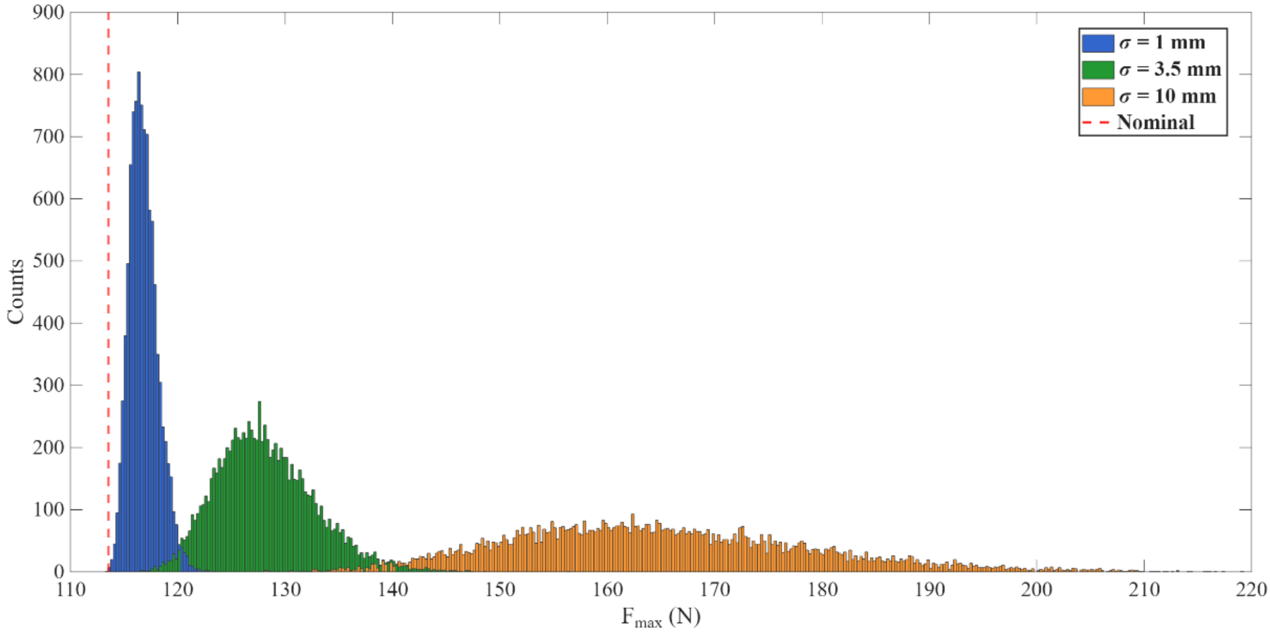

Figure 5: Histograms of the maximum contact force for three different levels of installation errors.

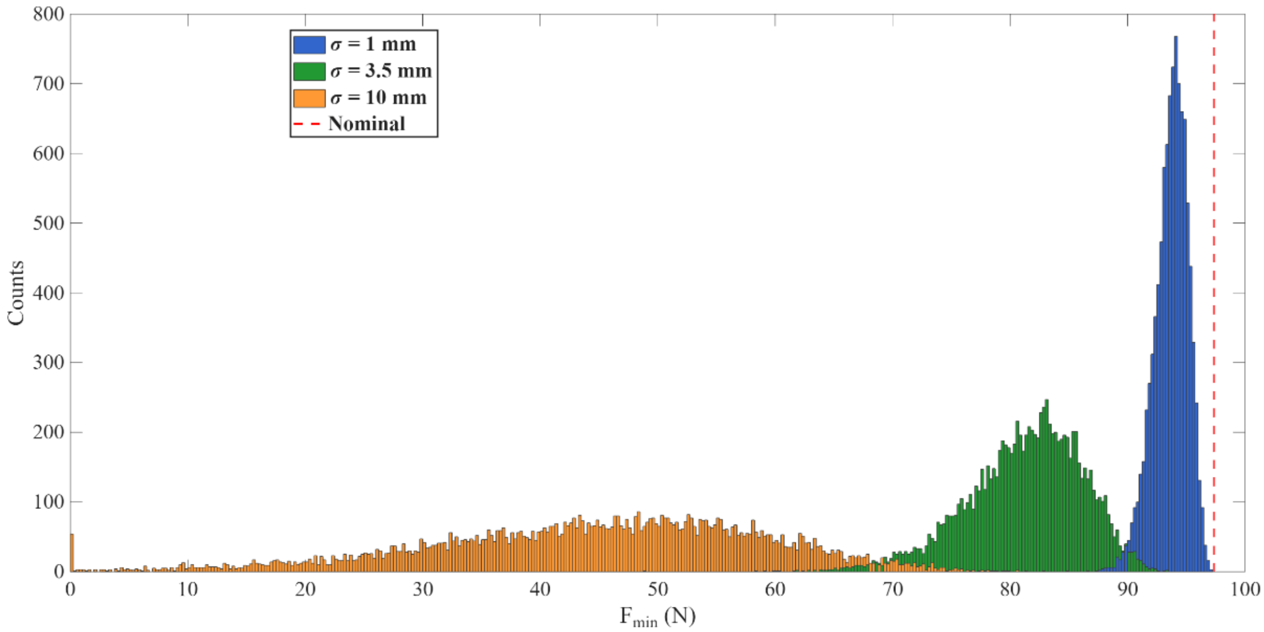

Figure 6: Histograms of the minimum contact force for three different levels of installation errors.

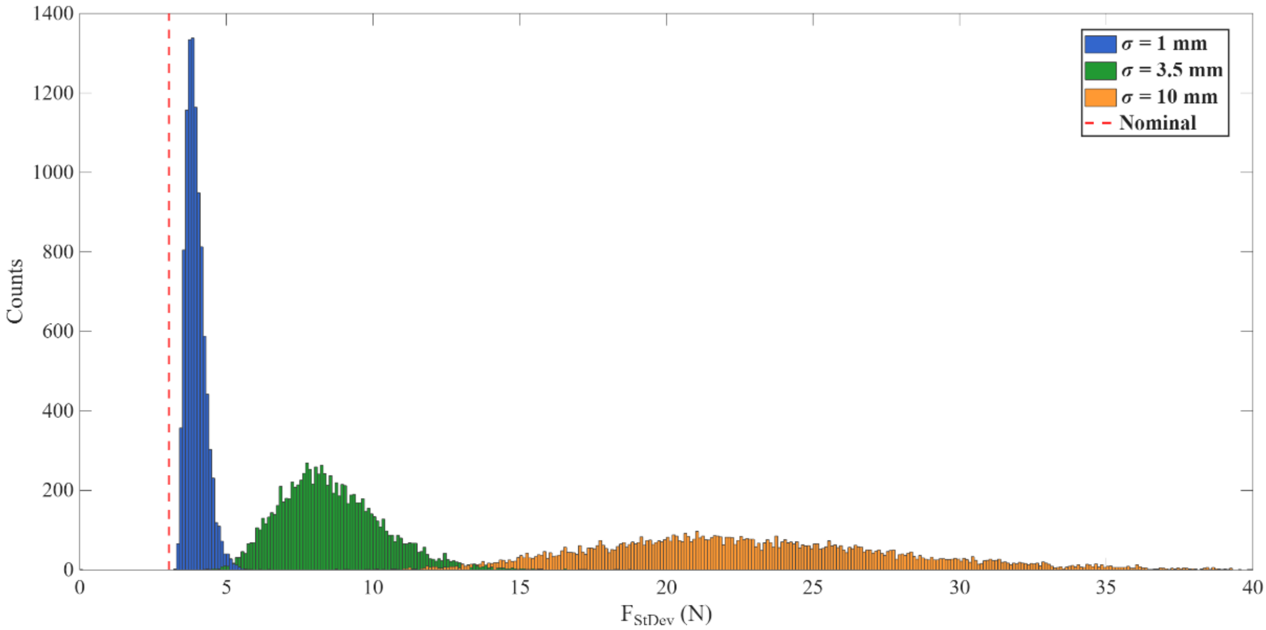

Figure 7: Histograms of the contact force standard deviation for three different levels of installation errors.

It is observed that the higher the installation errors allowed, the higher the contact force fluctuations are, which means higher contact force maxima, lower contact force minima, and an increase in the standard deviation. It is notorious that any of the 30000 cases analysed show a contact force whose standard deviation is below the nominal case. Increases in contact force fluctuations produce both greater contact wire and pantograph strip wear, and an increase in the probability of contact loss between the pantograph and the OCR, creating electric arcs that further damage both structures. Since the lowest contact force standard deviation stems from the nominal case, it is implied that an assembly without any sort of height offsets is the most beneficial. This behaviour contrasts with that exhibited by the flexible catenary, in which an appropriate combination of height offsets can reduce contact force fluctuations [12].

The contact force fluctuations increase substantially as assembly errors become more prevalent. A statistically average case of the dataset with $\sigma = 1$ mm has a range of variation of around 25 N between maximum and minimum contact force. That range increases to 55 N when $\sigma = 3.5$ mm and up to 140 N in the $\sigma = 10$ mm cases. Some fringe cases in the dataset with the highest magnitude of assembly errors yield a maximum contact force of 220 N, almost double the value of the maximum contact force in the nominal case (113.6 N). An especially relevant result is the minimum value of 0 N observed in Figure 6. A total of 206 simulations in the $\sigma = 10$ mm dataset (2.06% of the total) yielded a minimum contact force of 0 N in the simulation, implying that the pantograph and the catenary detached at a given point of the track.

4 Conclusions and Contributions

This work has analysed the effects of assembly errors on the pantograph–OCR interaction by means of thousands of numerical simulations with different levels of error. The results show a high sensitivity of the contact force to variations in support height, such that greater irregularity in support heights leads to larger fluctuations in the pantograph–catenary contact force. For the OCR studied in this work, these fluctuations can increase by more than a factor of seven compared to the nominal case in which no assembly errors are present.

In all 30 000 OCR simulations, the presence of support height offsets led to higher contact force fluctuations. Therefore, the results indicate that an OCR with uniform support height is the most appropriate in terms of current collection quality. As this is not achievable in practice, the results suggest that a maximum tolerance of ±3 cm is recommended to guarantee high performance in the pantograph–OCR dynamic interaction.

The methodology described in this paper provides a basis for quantifying the range of variation in contact forces when assembly errors are considered. Further work will focus on analysing other types of assembly errors and considering more realistic OCR sections, including uneven support spacing and overlap sections.

Acknowledgements

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