Dynamic simulation of the system pantograph-catenary-vehicle-track

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Abstract

This paper presents anadvanced pantograph-catenary-vehicle-trackmodel which allows the coupled simulation of the complete system. The model developed is able to evaluate the contact force generated in the catenary-pantograph and wheel-track interactions. Nevertheless, this paper focuses on the possible influence of the vehicle-track system in the catenary-pantograph dynamic interaction. Moreover, the effects of considering track irregularities and short-bridge ways are analyzed.The techniques employed in the simulation are widely known and therefore the formulation of its equations is not studied in depth.

1. Introduction

In railway systems, the cantenary-pantograph interaction is the phenomenon responsible of the transmission and the raising of the electric energy from the power supply to the locomotive. The quality of this raising, the circulation speedand the maintainability of the infrastructuredepend on the design and the running of this system. There are many analysis of the dynamic behavior of the system, so it is worthy to mention the surveysrelated to this topic realized in [1,2], the simulation of the catenary-pantograph dynamics using a finite element method (FEM in the following) presented in [3], the simplified models which are developed in [4] and improved in [5] or the mathematical model of [6].

As far as the drive system of the most of trains is based on the wheel-track contact, the study of the global dynamic of this system is known as vehicle-track interaction. Obviously, the quality of this contact affects on the passenger comfort, the noise emission and the maintainability of the set amongst others. There exist many studies about the global dynamic of the vehicle-track set:using moving loads and moving elements in both works [7] and [8] respectively; while an analysis of this interaction and its influence on the traffic when trainspass over bridgesis presented in [9] and [10].

2. Catenary- Pantograph mode

The catenary model employed in this work is based on a FEM discretization of the catenary geometry (Figure 1). In order to reachan accurate performance of the cable system: the contact andmessenger wires that have been employed are based on a co-rotational beam formulation; while the droppers have been modeled with truss elements which present also a co-rotational formulation. Moreover, these elements are not capableto resist compression efforts, so the possible slackening of the droppers is taken into account. The catenary used in the simulations presented in this paper is the Re-250, which is employed in the Madrid-Sevillahigh speed service.

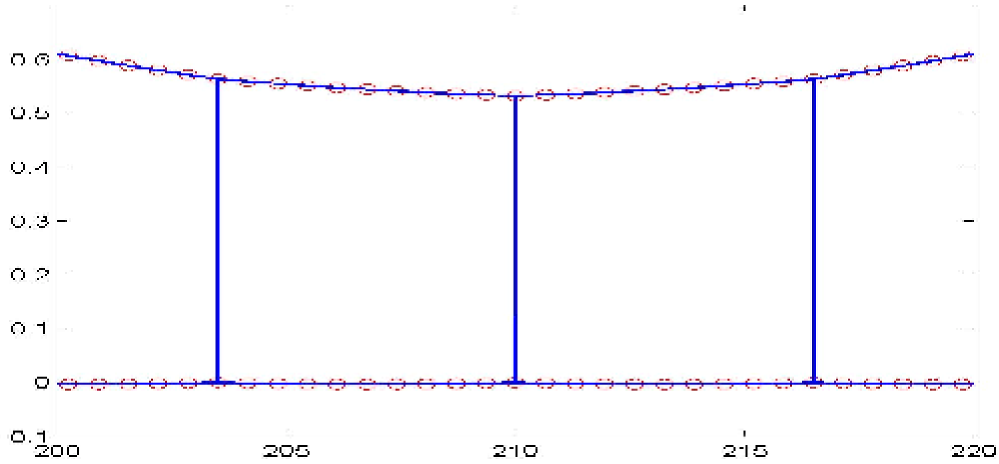

Figure 1. FEM mesh of a span of the catenary model

The pantograph model, on the contrary, has been carried out with a lumped-mass system, as it is usual in this kind of simulations,since its precision is generally enough. In addition, the pantograph has been preloadedwith a constant force of*157.3 N*.

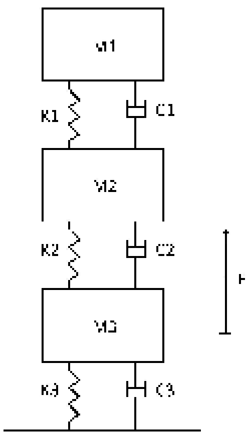

Figure 2. Pantograph model

The three-degrees-of-freedom pantograph depicted in Figure 2 has been simulated with the mass, damp and stiffness values collected in Table 1, which belong to the DSA-380E pantograph.Finally, the contact between the pantograph and the contact wire has been modeled using a penaltymethod, due to the simplicity of its implementation.

	1	2	3
M (kg)	6.6	5.8	5.8
C(Ns/m)	70	70	70
K(N/m)	$9.4 \cdot 10^3$	$14.1 \cdot 10^3$	0.08

Table 1: Simulation values of DSA-380E pantograph

2.1 Catenary-Pantograph interaction model

The dynamic performance of the catenary-pantograph system has been validated inaccordance with the European standard EN50318 [11]. This standard establishes the requirements for the validationof a catenary-pantograph interaction computational model. Essentially, this norm stablishes a benchmark theoretical cantenary-pantograph system and the range of results that must be accurately predicted by a simulation code. Table 2 showsa comparison of the obtained values over the referenced model previously described and the required by the aforementionedstandard.

Speed (km/h)	*250*		*300*	
	ValidationRange	*Model*	*ValidationRange*	*Model*
Mean contactforce (N)	110 – 120	116.07	110 – 120	115.35
Standard Desviation (N)	26 – 31	27.38	32 – 40	33.64
Max.Statistic value (N)	190 – 210	198.20	210 – 230	216.27
Min. Statistic value(N)	20 – 40	33.91	-5 – 20	14.44
Max. Real value (N)	175 – 210	177.57	190 – 225	210.35
Min. Real value (N)	50 – 70	60.05	30 – 55	40.87
Max. uplift at support 1 (mm)		53.4		62.7
Max. uplift at support 2 (mm)	48 – 55	51.9	55 – 65	63.1
Max. uplift at support 3 (mm)		53.0		62.0
Percentage of the loss of contact	0 %	0 %	0 %	0 %

Table 2: Validation of the catenary-pantograph model

3. Vehicle model

The vehicle model has been carried out with a ten-degrees-of-freedomlumped-mass system linked by truss bars as is shown in the diagram shown in Figure 3. This sort of models behaves more accurately than the simpler ones of three-degrees-of-freedom without an excessive added computational cost. Moreover, its modular nature allows fitting the lower part of the pantograph and the upper part of the vehicle by means of imposing that both displacements are equal.

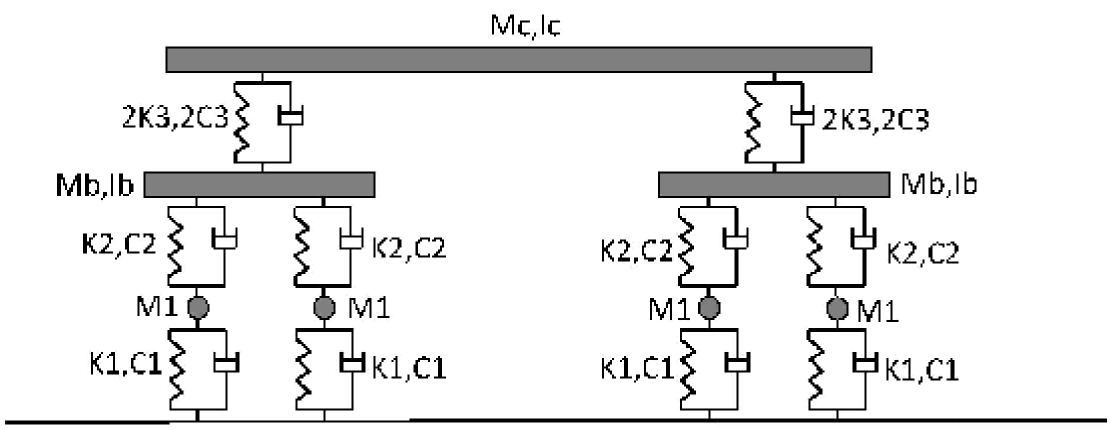

Figure 3.10 DOF vehicle model

Their stiffness and inertia values have been taken equivalent to the vehicles simulated.Thus in the simulations carried out, thevalues collected in Table 3, which belong to the 103 series of AVE trainstaken from [13,14], have been used.

	1	2	3
M (kg)	350	0	0
C(Ns/m)	$6.7 \cdot 10^5$	0	0.4
K(N/m)	$8 \cdot 10^9$	$0.3 \cdot 10^6$	$4.4 \cdot 10^6$
m_b (kg)	$5.84 \cdot 10^4$		
$I_b(m^4)$	$1 \cdot 10^{-3}$		
m_c (kg)	$6.19 \cdot 10^4$		
$I_c(m^4)$	$1 \cdot 10^{-3}$		

Table 3: Numeric values of the 103 serie of AVE

4. Track model

The track model has been realized by a beam over an elastic foundation as seen in Figure 4.Its stiffness gathers the most important features of the track. This makes it possible to simulate changes of the subsoil conditions, through varying the stiffness of the springs, or the addition of surface defects on the railsby modifying the geometric position of the beams.

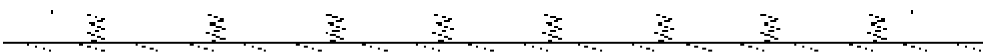

Figure 4. Track model

Real values of the Madrid-Barcelona high speed service, see Table 4, have been considered in the simulations that are presented in this paper.

Track	*Value*
E (GPa)	210
I (cm^4)	3313
A (cm^2)	28
ρ (kg/m^3)	7800
Platform	
K (MN/m)	15.79
Distancebetweensleepers (m)	0.6

Table 4.Properties of the rail and platformconsidered

The studyabout french trackscarried out by Frýba,presented in [12], shows that irregularities of a track can be considered as a random variable whose power spectral density function depends on the quality of the track. So, the different types of tracks are split up from the lowest (1) to the highest (6) quality class which characterizes this random variable.It is also possible to include variations on the theoretical position of the track by the generation of a spatial series whose power spectral density is:

$$PSD_{ir}(\omega_j) = \frac{A\omega_2^2(\omega_j^2 + \omega_1^2)}{\omega_j^4(\omega_j^2 + \omega_2^2)}$$

where the parameters*A,* ω_1, ω_2 depend on the quality of the track, see Table 5.Thus, once the theoretical random positions are generated it is possible to consider the position of the track from a more realistic point of view.

Class	*1*	*2*	*3*	*4*	*5*	*6*
A(mm)	15.53	8.85	4.92	2.75	1.57	0.98
ω_1	23.3					
ω_2	13.1					

Table 5: Values for the random irregularities simulation

Figure 5shows the power spectral density function and two series of irregularities compatible with the spectrum for two different class of track.

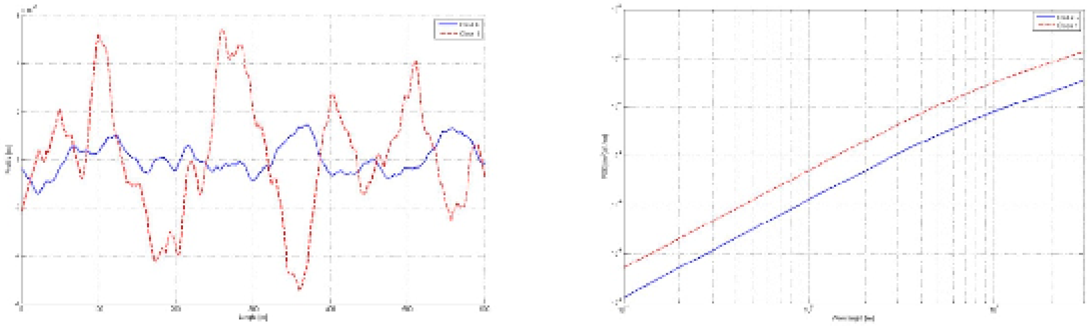

Figure 5. Random profiles and PSD functions

Likewise, it is possible to simulate the traffic of the vehicle over viaducts, which are modeledas the beam depicted in Figure 6in case of having short viaducts or by using amore complex FEM modelsin case of having longer viaducts.

Figure 6. Track and short bridge model

The short viaducts presented in this paper have been simulated with thepropertiesreferred in [13], which are reproduced in the following Table 6.

Length (m)	*E (GPa)*	*A (m^2)*	*I (m^4)*	*ρ (kg/m^3)*
5	29.43	0.8974	0.0154	7800
7.5	29.43	1.1538	0.0565	7800
10	29.43	1.2821	0.0881	7800
20	29.43	2.5641	1.7214	7800

Table 6: Characteristic values for short viaducts

4.1 Vehicle-Trackinteraction model

The set vehicle-track model has been validated by means of a reference simulation and the comparison of the obtained results against the values gathered in [8].Figure 7reflectsthis comparison: the displacements of the track that have been calculated using the model presented in this paper and the values obtained from the previously mentioned one.

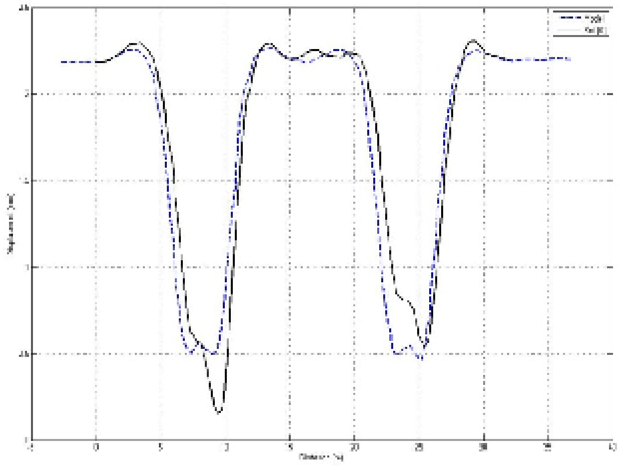

Figure 7. Validation of the vehicle-track model

5. Simulations and results

Both simulations of the catenary-pantograph set (CP), without considering the vehicle-track set, and simulations that take into account this set and the existence of random irregularities and the traffic over short viaducts have been realized. So, for the last one a coupled model catenary-pantograph-vehicle-track (CPVT)has been carried out as it is represented inFigure 8.

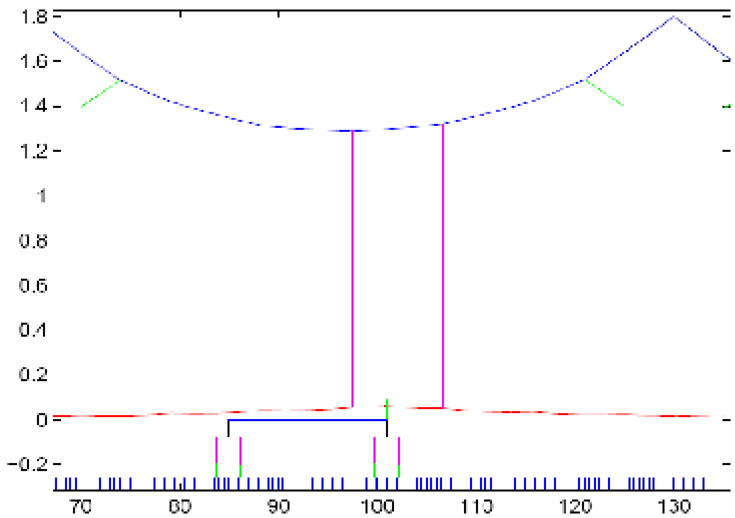

Figure 8.Coupled model CPVT

The basic isolated simulation of the catenary-pantographdynamic interaction establishes the reference point of this study. Afterwards, these simulation values will be useful to analyze the effect of the vehicle-track model over the catenary-pantograph dynamics. This dynamic interaction has been performed applying a time integration scheme α-generalized,obtaining the following results of Table 7:

Speed(km/h)	200	250	300	325
MinimumContactForce(N)	69.55	57.33	45.04	29.03
MaximumContactForce(N)	165.78	208.89	218.7	227.91
MeanContactForce(N)	120.14	119.93	119.63	118.55
Standard desviationContact Force (N)	18.98	25.37	30.342	35.74
Rangepantographdisplacement (mm)	31.4	26.4	28.3	30.6

Table 7: Values of the catenary pantograph simulation

5.1 Track Irregularities

The results of the coupled simulation CPVT using a track with random irregularities of quality class 6are shown in Table 8. This table presents the values of contact force and contact point displacement historyfor each traffic speed. Moreover, the percentage difference with the reference point of Table 7 is also tabulated for each case.

Speed (km/h)	200		250		300		325	
Mean C.F. (N)	120.56	0.35%	119.6	-0.28%	119.99	0.30%	118.86	0.26%
Maximum C.F. (N)	169.9	2.42%	211.64	1.30%	219.15	0.21%	227.79	-0.05%
Minimum C. F.(N)	70.78	1.74%	53.14	-7.88%	45.33	0.64%	29.51	1.63%
Standard Desv. C.F. (N)	19.41	2.22%	25.69	1.25%	30.25	-0.3%	36.05	0.86%
Range panto. Disp (mm)	29.00	8.28%	28.82	8.40%	30.34	6.72%	32.97	7.19%

Table 8: Values of the simulation CPVT with random irregularities

The influence of the track profile in the response of the vehicle can be seen in Figure 9, where the response of the top of the vehicle is showed in a track without irregularities together with two different random profiles of irregularities of quality class 1. The presence of these irregularities increases the displacements of the vehicle.

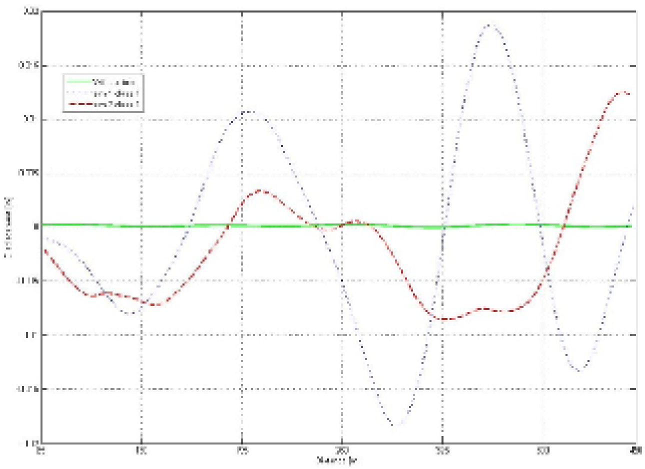

Figure 9. Vehicle response for different track profiles

The following figure, divided into two subfigures, illustrates a pantograph displacement comparison.Inthe left side of Figure 10is depicted the vertical displacement of the contact point,which is almost the same considering the system catenary-pantograph with and without the system vehicle-track(note that the red line overlapsthe blue one). The right side of thisfigure shows the differences in the pantograph displacements among different kind of trackquality classes. The displacement conservesits basic tendency althoughlittle differences in amplitude can be observed.

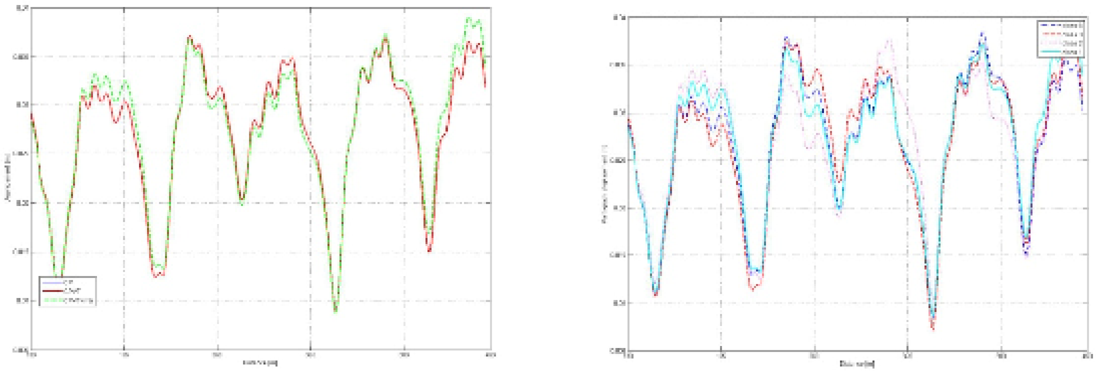

Figure 10.Pantograph displacement comparison

Figure 10 and particularly Figure 11 also show that the frequency contain of the signal is not modified for the presence of the system vehicle-track. Thus, Figure 11 presents the spectrum of the pantograph displacement.

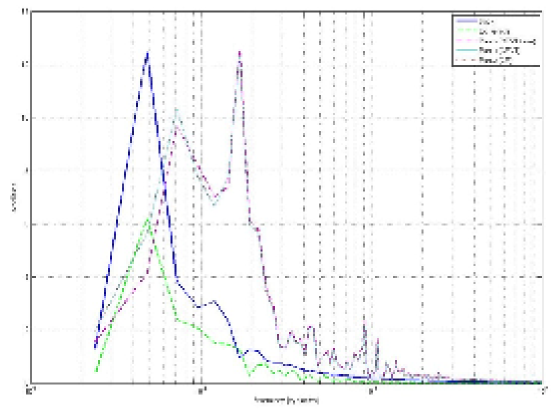

Figure 11. Pantograph displacement spectrum

5.2 Short Bridges

The simulations that have been performed considering the traffic over short bridges have been compared with the results of the contact force in the case of just simulating the set CP. The percentage differences are contained in Table 9.

Length (m)	5	7.5	10	20	*Speed(km/h)*
Minimum	-0.31	-1.14	-2.88	-5.47	200
Maximum	0.35	0.96	2.8	3.98	
Standard Desv	0.11	0.23	0.56	1.13	
Range	0.66	2.1	5.78	9.45	
Minimum	-0.6	-0.75	-1.92	-3.44	250
Maximum	0.98	1.30	2.55	3.3	
Standard Desv	0.36	0.45	0.92	1.47	
Range	1.58	2.06	4.47	6.74	
Minimum	-1.82	-1.15	-2.04	3.14	300
Maximum	1.11	1.23	1.97	3.22	
Standard Desv	0.41	0.32	0.53	0.98	
Range	2.92	2.37	4.01	6.36	
Minimum	-0.71	-1.01	-0.64	-2.86	325
Maximum	0.74	0.75	1.26	3.28	
Standard Desv	0.16	0.16	0.78	1.01	
Range	1.45	1.75	1.91	6.14	

Table 9: Differences [%] in the traffic over short bridges

6. Conclusions

In view of the results presented on the previous sections, it is possible to conclude that the vehicle-track system introduces differences lower than 3% in the contact force of the catenary-pantograph interaction due to track irregularities.Thus,although these differences can be neglected, the displacements in the pantograph reach differences between 6% and 8% in the worstquality class of the track.However, these differences would be decreased in case of consideringhigher quality of the track. In case of considering the traffic over short viaducts the differences can be up to 10%.

7. Acknowledgements

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ɘed (km/h)	200		250		300		325	
Maximum (N)	212.6	1.51%	257.6	4.67%	246.9	1.03%	268.9	5.39%
Minimum(N)	98.41	-1.08%	71.31	-23.2%	69.45	-1.22%	48.66	15.22%
Standard Desv. (N)	22.97	2.83%	31.36	-22.5%	31.61	0.69%	39.7	4.15%
Range (N)	114.14	3.64%	186.29	21.54%	177.45	1.99%	220.24	2.91%

Table 10: Values of the simulation CPVT over large bridges