Dynamic pantograph behaviour on high-speed electric locomotives

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Abstract. When driving high-speed electric locomotives, the aerodynamic component can no longer be neglected. This component influences the interaction between the pantograph and the catenary by further loading or unloading the downforce of the pantograph on the contact wire. The paper aims to determine the additional forces required by the pantograph and to determine the effects of these demands on the dynamic behaviour of the pantograph. This analysis is important because the aerodynamic stresses exerted on the pantograph can cause the contact force to drop on the contact wire, which may result in the detachment of the catenary current collector. The effects of the loss of contact between the pantograph sleeve and the contact line has direct consequences on the operation of the electrical circuits on the locomotive, especially the force circuits, given their capacitive and inductive loads. Through this study we aim to determine if negative effects cannot be converted into positive effects through a constructive solution of the current collector.

1. Introduction
As it is specified in the railway literature [1-4], the electric vehicles can move only if the necessary electric energy is retrieved from an exterior power source (from the power line – catenary), situated outside the vehicle. In the case of electric trains or for the electric locomotives, the pantograph is used for retrieving electric energy, and they are situated on the roof of the vehicle [1-4]. As such, the role of that equipment is to pick the required energy needed for the movement of the railway vehicle and transmit it to the traction system inside the vehicle. This is possible only if a proper sliding contact between the pantograph contact wire is maintained.

As the railway traction vehicles moving speeds are getting higher, maintain a good contact is more difficult whereas aerodynamic forces occur and excitements of the catenary or pantograph grip system occurs.

2. Forces that occur in the catenary-pantograph contact
For the beginning, we will analyse how do aerodynamic forces influence the proper maintaining catenary contact. In this regard, we start from the general formula that determines the forward resistances for the railway vehicles, which is known as the Davis’s formula [1-13]:

\[ R_f = a + b \cdot v + c \cdot v^2 \] (1)
where: $R_t$ – overall forward-facing resistance force of the vehicle; $a$ – mechanical rolling resistance caused by axle loads; $b \cdot v$ – non-aerodynamic forward-facing resistance force; $b \cdot v^2$ – aerodynamic forward-facing resistance force; $v$ – the speed of the vehicle.

As it can be seen, the aerodynamic component of the overall forward-facing resistance force of the vehicle is directly proportional to the square of the moving speed. The formula for explaining the “c” parameter for the aerodynamic resistance, according to the literature is:

$$c = \frac{C_x \cdot S \cdot \rho}{2}$$

where: $C_x=2\cdot F/S \cdot v^2$ – the aerodynamic coefficient of sliding air, also known as the air penetration coefficient (dimensionless); $S$ – the front area of the vehicle in cross-section (m$^2$); $\rho$ – the density of the air in which the vehicle is traveling (kg/m$^3$); $F_x$ – the front aerodynamic force strength (N); $v$ – fluid velocity (air) (m/s).

On the railway vehicle body, there are possible two distinctive situations for using the active pantograph. The difference between those two cases is how the joint between the pantograph arms are positioned, so:

- when the joint between the pantograph arms are positioned in the same way as air flow, it is facing backwards to the moving vehicle direction (figure 1);
- when the joint between the pantograph arms are positioned opposite sense of air flow, it is indicating the direction of the moving vehicle (figure 2);

![Figure 1](image1.png)  
**Figure 1.** Pantograph with the tip of the joint angle in the direction of air flow – Pd1.

![Figure 2](image2.png)  
**Figure 2.** Pantograph with the tip of the joint angle in the opposite direction of air flow – Pd2.
In the papers [1, 12, 14] are presented a method based on the study of the balance of forces and moments which acts on the components of the pantograph. According to this method, the aerodynamic forces acting on the pantograph components are evaluated on the basis of the corresponding aerodynamic coefficients, so:

\[ F_{x pj} = \frac{\rho \cdot (C_x \cdot S_p)_{j} \cdot v_{rel,p}^2}{2} \]

\[ F_{z pj} = \frac{\rho \cdot (C_z \cdot S_p)_{j} \cdot v_{rel,p}^2}{2} \]

\[ M_{ijp} = \frac{\rho \cdot (C_m \cdot S_p \cdot l_p)_{j} \cdot v_{rel,p}^2}{2} \]

where: i – index on the Cartesian coordinate system axes; j – index of pantograph components; \( F_{x pj} \), \( F_{z pj} \) – the aerodynamic forces in the longitudinal and vertical direction corresponding to each component of the pantograph; \( M_{ijp} \) – the moments of forces corresponding to each axis of the Cartesian system; \( v_{rel,p} \) – the relative velocity of flow of fluid between pantograph elements; \( (C_x \cdot S_p)_{j} \), \( (C_z \cdot S_p)_{j} \) and \( (C_m \cdot S_p \cdot l_p)_{j} \) – the pressure coefficients for the frontal, and vertical, aerodynamic resistance, as well as the resulting torques for each j element in which the pantograph was divided.

To determine aerodynamic force values, the geometric shape of the pantograph scale 1:1, was modelled using Autodesk Inventor. The height of the raised pantograph was constantly maintained at the maximum admissible value according to the technical specification, at which the pantograph collector head can capture current from the 2.5 m contact line. Airflow simulation was performed using the SolidWorks Flow Simulation software.

In the airflow analysis process, the relative air speed considered corresponds to the situation when the vehicle is moving at a constant speed of 144 km/h = 40 m/s.

The airflow is simulated in a volume delimited as following:
- in the vertical plane we considered the plan of the vehicle body roof and another plan situated at 6 meters from it,
- for the cross-section, we considered two planes located symmetrically 5 m from the longitudinal plane of the vehicle,
- for the longitudinal section, we considered two planes situated 5 m and 10 m from the pantograph chassis transverse plane.

The first plane of the longitudinal sections (5 m) corresponds to the front of the locomotive in the direction of the air flow and the second plane of the section (at 10 m) of the rear part of the vehicle.

Other input parameters used in the flow simulation were considered appropriate for the vehicle's moving situation under normal atmospheric pressure and temperature conditions as can be seen in table 1.

| Units | Values     |
|-------|------------|
| Pressure | PA 101325  |
| Temperature | K 293.2    |

Stabilized values of the aerodynamic forces resulted from the simulations performed in the two pantograph positioning situations are presented in table 2.
### Table 2. Aerodynamic forces.

| Units | Type of positioning |
|-------|---------------------|
|       | Pd1     | Pd2     |
| Speed | m/s     | 40      | 50      |
| F_{z,tot} | N      | 248.48  | 406.37  |
| F_{a,x}  | N      | 247.72  | 406.33  |
| F_{a,y}  | N      | 0.48    | 5.69    |
| F_{a,z}  | N      | -19.41  | -0.65   |

### 3. Simulation of pantograph-contact line interaction

Increasing traffic speeds imposed by the need to increase passenger and freight mobility are leading to new approaches to studying pantograph-contact lines interaction. The study of effects on high-speed traffic determines useful design solutions to provide the rail traction vehicle with optimum energy capture conditions. Practical experience shows that simulation models allow full study of the interaction effects of subsystems characteristic of pantograph contact line assembly. From this perspective, the evaluation of the different subsystems is based on the effects of the variations of the parameters specific to the current collector construction.

The pantograph-catenary contact force is the objective of dynamic simulations. Validation of the models used must allow for the analysis of parameters more easily measured than the contact force, such as accelerations, displacements. The design of the contact line must take into account a number of characteristics specific to its construction, such as: the type of contact wire, the line-specific elements, the dynamic characteristics of the structural members, the discontinuities, the tensioning points.

If we are talking about pantograph, the model must take into account the types of mechanisms and their characteristics and, also, the types of contact elements.

The modelling must allow the parameters of the studied subsystems to be modified in order to allow system design optimization (pantograph, contact line), considering also that the pantograph and the contact line are two independent systems that can oscillate independently, and can also become coupled by the force of contact, in the contact point.

This article presents the study for the dynamics of the pantograph under the influence of the aerodynamic effect according to the elastic parameters of the system considered.

For modelling the pantograph, we used a model with three masses corresponding to the lower arm, the upper arm and the collector head, coupled by springs and dampers, figure 3, resulting from the analytical model, figure 4. The model with three oscillating masses is the most commonly used.

![Figure 3. Modeling of the pantograph with three masses connected by spring and dampers.](image-url)
MapleSim version 16 software was used for modeling and simulating the three-mass model pantograph. The modeling scheme is shown in figure 5.

The simulations were made to determine the dynamic behavior of the pantograph according to the parameters of the oscillating system (elasticity constant $k$ and stiffness constant $c$), but also to see the influence of the aerodynamic force on the pantograph dynamics at the speeds between 140 and 180km/h. The study is designed for EP3 pantographs of the 060 EA electric locomotive.

The simulations focused on varying the stiffness constant because this parameter influences the pantograph dynamics the most. For study, a variation of the parameters is considered to be $\pm 50\%$ of the initial value (table 3). Simulations were also performed for three frequencies of pantograph contact force (0.74 Hz, 0.96 Hz and 1.15 Hz respectively).
Table 3. Aerodynamic forces.

| Units       | Modify % | C1   | Modify % | C2   |
|-------------|----------|------|----------|------|
| Initial     | Ns/m     | 0    | 48       | 0    | 48   |
| Case 1      | Ns/m     | +50  | 72       | +50  | 72   |
| Case 2      | Ns/m     | -50  | 24       | -50  | 24   |
| Case 3      | Ns/m     | +50  | 72       | +50  | 72   |
| Case 4      | Ns/m     | -50  | 24       | +50  | 450  |
| Case 5      | Ns/m     | +50  | 72       | 0    | 300  |
| Case 6      | Ns/m     | -50  | 24       | 0    | 300  |
| Case 7      | Ns/m     | 0    | 48       | -50  | 150  |
| Case 8      | Ns/m     | 0    | 48       | +50  | 450  |

Figure 6 shows the amplitudes of accelerations when the elastic and damping elements have the initial values. The force is harmonic sinusoidal with the amplitude of 50 N and the maximum pantograph contact wire force does not exceed 100 N and the minimum value does not allow the phenomenon of pantograph detachment from the contact line. It can be seen that the greatest oscillations are at the level of the collector head. Also, the most powerful transient regimes are at the beginning of the simulation, and the movement will stabilize and become periodic.

Figure 6. MapleSim simulation model of the EP3 pantograph.

The amplitude of the accelerations also increases due to the variation in the positive sense of the contact force frequency, as can be seen in figure 7. By integrating the accelerations twice, the pantograph movement will be obtained, which will be more pronounced at higher frequencies of the excitation force. Frequencies of the contact force were chosen to be the values of the natural frequencies of the contact wire.

The influence of stiffness constants may lead to an improvement or degradation of the pantograph dynamic regime. A particular influence is if the stiffening of the base is raised, which reduces the pantograph oscillation amplitudes. The best oscillation attenuation is obtained when the stiffness of the base increases with the same order of magnitude of the decreasing stiffness of the collector head suspension (figure 8), or when both grow with the same order of magnitude. Opposite results are obtained with the reduction of the rigidity of the base with an almost insensible influence of the differences due to the increase or decrease of the stiffness of the collecting head suspension. The influence of rigidity of the pantograph shoes suspension is almost negligible if the rigidity of the base remains the initial one.
Figure 7. Accelerators of the pantograph elements for frequencies of 0.74 Hz, 0.96 Hz, 1.15 Hz for lower arm, upper arm and collector head.

Figure 8. Deviations from the initial acceleration averages (for each case).

Regarding the influence of additional aerodynamic force, it affects the dynamics of the pantograph only during the transitional period. Increasing or decreasing the contact force relative to the initial conditions, where no additional aerodynamic forces are present, influences the acceleration amplitude proportionally (figures 9). When the motion becomes stable and periodic, the acceleration amplitudes overlap with the initial one (figure 10, 11 and 12).

Figure 9. Collector head transitory regime with aerodynamic forces at 0.74 Hz.
Figure 10. Influence of aerodynamic forces on the acceleration of the pantograph components for initial force frequency at 0.74 Hz.
Figure 11. Influence of aerodynamic forces on the acceleration of the pantograph components for initial force frequency at 0.96 Hz.
Figure 12. Influence of aerodynamic forces on the acceleration of the pantograph components for initial force frequency at 1.15 Hz.
4. Conclusions
In railway electric vehicles, two distinct situations regarding the layout of the asymmetrical active pantograph can be encountered, as can be seen from figures 1 and 2.

During the movement of the vehicles, on the active pantograph components will actuate the aerodynamic forces that will be directed both in the vertical direction and in the horizontal transversal direction, as shown in relations 3, 4 and 5. From the point of view of the pantograph-catenary loads, the vertical forces are of interest.

In order to be able to see the values of the vertical forces caused by the action of the air on an asymmetrical active pantograph (while moving electric vehicles), such equipment was modelled first, using Autodesk Inventor. With the geometric 3D model obtained, was used to simulate airflow with the program SolidWorks Flow Simulation.

Airflow simulation is performed for two values of the traveling speed of railway electric vehicles at normal atmospheric conditions (no gusts) and with the air characteristics shown in table 1.

Based on the simulated initial simulation conditions, the results obtained on the aerodynamic force values and its decomposition on the three directions of the Cartesian axis system were centralized in table 2.

Additional pantograph loading at 140-180 km/h is 27 ÷ 40 N in the direction of increasing the contact force of the rear pantograph due to the increase in the vertical force component $F_z$, is an advantage for a better contact between pantograph and wire, but it is a disadvantage from the point of view of the mechanical use of the collecting head.

For the front pantograph, a discharge is noted, which can lead to accidental detachment from the contact wire at medium speeds (90-110 km/h).

From the point of view of the influence of stiffness of the pantograph joints, the major influence of the rigidity between the lower arm and the base is observed. Its additional hardening results in less acceleration amplitudes. Hardening the patina suspension has a reduced influence on the accelerations if the rigidity of the base remains unchanged.

The overlapping of additional force due to the influence of the aerodynamic forces has a consequence during the transitory period through a proportional variation of the system acceleration; when the movement becomes periodic, the amplitudes of the accelerations obtained overlap with the initial acceleration.

5. References
[1] Arsene S, Sebeşan I and Popa G 2015 The Influence of Wind on the Pantograph Placed on the Railway Electric Vehicles Bodywork Procedia - Social and Behavioral Sciences vol 186 pp 1087 – 1094
[2] Sebeşan I, Arsene S and Stoica C 2013 Experimental study on determination of aerodynamic resistance to progress for electric locomotive LE 060 EA1 of 5100 kW Scientific Bulletin-University Politehnica of Bucharest, Series D vol 75 no 4 pp 85-96
[3] Sebesan I, Arsene S, and Stoica C 2013 Experimental analysis for aerodynamic drag of the electric locomotives Incas Bulletin vol 5 Issue 3 pp 99-115
[4] Sebesan I and Arsene S 2014 Study on aerodynamic resistance to electric rail vehicles generated by the power supply Incas Bulletin vol 6 Special Issue 1 pp 151 – 158
[5] Raghunathan R S, Kim H D and Setoguch T 2002 Aerodynamics of high-speed railway train Progress in Aerospace Sciences vol. 38 Issues 6–7 pp 469–514
[6] Lukaszewicz P and Andersson E 2009 Green Train energy consumption Estimations on high-speed rail operations KTH Railway Group Stockholm 2009
[7] Kiessling F, Puschnmann R and Schmieder A 2001 Contact lines for electric railways: planning, design, implementation Publicis
[8] Popa G, Arsene S and Mihailescu M 2012 Startup railway vehicles with asynchronous traction
motors Electrical Systems for Aircraft, Railway and Ship Propulsion Bologna 2012 pp 171 – 176

[9] Popa G, Mihaiescu M and Arsene S 2012 Contact line oscillations induced by the pantograph coupling, Electrical Systems for Aircraft, Railway and Ship Propulsion Bologna 2012 pp 181 – 186

[10] Arsene S and Sebesan I 2015 Analysis of the wind influence on the aerodynamic drag in the case of a certain emplacement of the pantograph on the electric rail vehicles Incas Bulletin vol 7 Issue 1 pp 3-12

[11] Sebeșan I and Arsene S 2015 Considerations on dynamic contact force with catenary for the EP3 pantograph Applied Mechanics and Materials vols 809-810 pp 1121-1126

[12] Arsene S 2015 The vertical forces introduced by wind on the active pantograph from bodywork of locomotive LE 060 EA of 5100 kW Applied Mechanics and Materials vols 809-810 pp 1115-1120

[13] Sebesan I and Arsene S 2012 Considerations on study the aerodynamic of pantographs railway vehicles International Conference of Aerospace Sciences Bucharest 2012 pp 397-402

[14] Pombo J, Ambrósio J, Pereira M, Rauter F, Collina A and Facchinetti A 2009 Influence of the aerodynamic forces on the pantograph–catenary system for high-speed trains Vehicle System Dynamics vol 47 no 11 pp 1327–1347