ABOUT THE PANTOGRAPH-CATENARY INTERACTION ON PORTUGUESE RAILWAYS

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ABSTRACT

A good electrical contact in the pantograph-catenary system is a fundamental aspect in electrical locomotives as well as the control of the factors, which affect it. On the other hand, the design and construction of the pantographs must be sufficiently reliable so as not to cause premature breakdowns and accidents.

The College of Transports (ISTP) was entrusted by Portuguese Railways to undertake a R&D project which is currently under way. We hereby present some of the results regarding the dynamic analysis of the elastic system pantograph-catenary and a forecast of its behaviour in service. The main causes of the accidents, which have occurred over the last years sometimes leading to the destruction of the pantograph and important lengths of catenary, were also detected.

1 – INTRODUCTION

The work on which this paper is based follows a request by Portuguese Railways.

It is a problem which has caused various interruptions in the circulation of rolling stock for the company due to track blockages as well as physical accidents involving the destruction of pantographs and important lengths of catenaries.

Therefore, in this project, we intend to better understand the dynamics of the process in trains with speeds of up to 220 Km/h. We also intend to know better which parameters should be chosen and controlled so as to obtain a good electrical contact between the pantographs and the OHEC (Overhead electrical conductors).

This choice and the control applies both to new pantographs and to those which have been repaired or serviced.

From a mechanical point of view, the design, construction and repair of pantographs must be sufficiently reliable so as to avoid premature breakdowns and accidents.

We hereby present some of the results

regarding the dynamic analysis of the elastic system of the pantograph-catenary and a forecast of its behaviour in service.

The main causes of the related accidents which have occurred over the last years and which lead to the destruction of pantographs and important lengths of catenary were also discovered and are given.

2 – DYNAMIC ANALYSIS OF THE PANTOGRAPH CATENARY INTERACTION

2.1. Description of the catenaries and pantographs in service in Portuguese Railways

A. Catenary

The Portuguese Railways network has not yet been totally electrified, possibly due to the low density of traffic on most of the system. One of the first lines to be electrified links the country's two main cities, Lisbon and Oporto and also serves some important towns and two major junctions. As a consequence, this 300 Km long line which is built in double track, has a relatively high density and the fasted trains which run on it at the moment can complete a non-stop journey in 3 hours between the two cities. This means that they are averaging about 100 Km/h.

The line was electrified at 25kV-AC in the mid fifties and has been upgraded several times over the years. We can consider that at the moment there are really 3 zones with maximum speed restrictions of just 70, 120 and 160 Km/h. The catenary is, however, being progressively modified, according to a project which was put out to SOFRERAIL, so as to enable it to support speeds of up 220 Km/h along its entire line. These modifications include:

a) The introduction of a pre-sag in the OHEC of 1/1000th of the distance between masts;

b) More resistant hanging wires, capable of supporting greater mechanical stresses;

c) Modification of the current format of the catenaries so as to eliminate the Y suspension;

d) Stretch forces of 12 000 N in the OHEC which is made of copper and has a 107 mm^2 profile. This force is the same as in the OHEC support cable which is made of bronze and has a profile of 56 mm^2.

The distance (pitch) between the masts is normally 63 m but this may be as little as 18.5 m in some places. The hanging wires are normally about 9 m apart but may be as close as 4.5 m to one another.

The catenary, after the modifications, and taking into account the stretch forces of the OHEC (T_c) and the support cable (T_s) both with 12 000 N and the respective masses per meter (m_{1c}=0.95 Kg/m and m_{1s}=0.58 Km/m), will have the following characteristics:

- Speed of wave propagation:

$$c=\sqrt{\frac{T_C}{m_{1c}}}=112m/s\equiv 403Km/h$$

- Doppler factor for v=220 Km/h:

$$\alpha=\frac{c-v}{c+v}=0.29$$

- Reflection factor:

$$r=\frac{\sqrt{T_s m_{1s}}}{\sqrt{T_s m_{1s}}+\sqrt{T_c m_{1c}}}=0.44$$

- Amplification factor:

$$\gamma=\frac{r}{\alpha}=1.3$$

The ERRI report A 186/RP1 recommends for high speed lines, $\alpha>0.15$ and r between 0.37 and 0.45. The amplification factor γ is less than the acceptable values of between 2.3 and 3.0.

B. Pantograph

The pantographs used in Portuguese Railways are supplied with the locomotives and most of them have the following characteristics:

- Service tension - 25 kV

- Normal zigzag of the OHEC - 2x200 mm

- Height when lowered - 550 mm

- Reach over lowered height - 2700 mm

- Maximum operating height - 2500 mm

- Minimum operating height - 300 mm

- Length of carbon contact strips (pantograph slippers) - 800 mm

- Distance between centres of carbon contacts - 360 mm

- Total width of panhead - 1450 mm

- Single arm made of steel tubing;

- Elastic suspension of panhead by two double rubber torsion arms;

- Torsion bar to maintain the panhead horizontal while following the level of the OHEC;

- Constant elevation force of the pantograph by spiral springs

The pantographs for the locomotives which have been delivered recently by the same supplier, have the same configuration as those above, but the upper arm is made of aluminium alloy. The distance between the centres of the carbon contacts is only 300 mm and the constant elevation force is guaranteed by a pneumatic mechanism.

Through drawings, other technical documents, observation, measurement and tests we have been able to calculate the following characteristics for the dynamic study of the pantographs:

Panhead mass - m_1=9.5 kg

Equivalent mass of the single arm mechanism in the torsion bar (estimated) - m_2=15 kg

Static contact load between the carbon strips and the OHEC - F_m=70N

Equivalent spring rate of the raising spring - $k_2 \cong 0$

Dry friction force in the single arm mechanism - S_2=±8N

Spring rate of the double rubber torsion arm mechanism at static deflection - k_{12}=8800 N/m

Damping rate of the double rubber torsion arm mechanism - C_{12}=40 Ns/m

We also estimate, for a merely qualitative analysis, that the equivalent mass of the OHEC is m_c=2 kg and that the OHEC spring rate is:

$$k_c = k_m + k_0 \cos\frac{2\pi v}{L}t \tag{1}$$

and, within the same criteria, that the value of the average spring rate of the OHEC is k_m=600 N/m, and that the variation amplitude of the spring rate in the OHEC between the masts (L), is k_o=200 N/m. As we stated above, v is the speed of the locomotive in m/s.

2.2 Dynamic model of the pantograph and the OHEC

The pantograph and the catenary together are a dynamic interactive system whose simplified physical model, as we propose, is given in figure 1.

It is our belief that the variable spring rate of the OHEC along the distance between the masts is the main cause of pantograph excitation. The form of k_c was established for an OHEC with no pre-sag and therefore a perfectly straight line and the values for k_m and k_o were defined without any worries about the real values but simply as a means of testing our model. This was also true for the value which we established for the equivalent mass of the OHEC on the panhead contacts.

There is, obviously, the aerodynamic effect of the wind, which becomes quite significant for speeds of over 160 km/h, but from the point of view of an eventual reduction in the contact force to levels which cause deficient transmission of electric current, we believe that wind gusts, which can cause panhead flutter, are much more dangerous.

However, our intention in presenting the dynamic study is at the end of the day, to make a theoretical forecast of the variation in the contact forces between the OHEC and the panhead along a journey, regardless of the wind force, and other irregularities such as rail deformity and the suspension of the OHEC itself.

If a pre-sag is introduced at the beginning of the OHEC so as to compensate for the lower spring rate in the central part, i.e. in the area which is raised most by the action of a constant force (Fm=70 N) the expressions given below become more complex but not so much that they cannot be done on computer.

2.3 Mathematical equations

The model in figure 1 is represented by the following differential equations:

$$(m_c + m_1)\frac{d^2\bar{x}_1}{dt^2} + C_{12}(\frac{d\bar{x}_1}{dt} - \frac{d\bar{x}_2}{dt}) + K_{12}(\bar{x}_1 - \bar{x}_2) + K_c\bar{x}_1 = 0$$

$$m_2\frac{d^2\bar{x}_2}{dt^2} + C_{12}(\frac{d\bar{x}_2}{dt} - \frac{d\bar{x}_1}{dt}) + K_{12}(\bar{x}_2 - \bar{x}_1) = 0 \qquad (2)$$

if we ignore the existence of dry friction force S_2 . The symbols $\bar{x}_1$ and $\bar{x}_2$ represent the dislocation of the masses ($m_c + m_1$) and m_2 from their static point of equilibrium, x_{1m} and x_{2m}. The equivalent force (F_e), which balances the force of gravity of the masses m_2 and m_1 and provokes the static force F_m can be determined by the equation

$$F_e = F_m + g(m_1 + m_2) = 310N \qquad (3)$$

and contributes to determining the static variations of x_1 and x_2:

$$F_e = m_2 g + k_{12}(x_{2m} - x_{1m}) \qquad (4)$$

The contact force (F) between the OHEC and the panhead can be expressed by

$$F = F_m + m_c\frac{d^2\bar{x}_1}{dt^2} + k_c\bar{x}_1 \qquad (5)$$

The component F_m may contribute towards determining the average static variation of the OHEC (x_{1m}).

In the simplified case in which C_{12}=0 and S_2=0, the average value of F may be written as

$$F_m = x_{1m}k_m + m_c g + a_1 k_0 / 2 \qquad (6)$$

and from here we can get x_{1m} even though we do not know the term a_1 which is part of the solution we want for x_1:

$$x_1 = x_{1m} + \sum_{i=1} a_i \cos\frac{2\pi i v}{L} \qquad (7)$$

In this simplified case, the second equation of (2) allows us to obtain

$$x_2 = x_{2m} + \sum_{i=1} \alpha_i a_i \cos\frac{2\pi iv}{L} \quad (8)$$

in which

$$\alpha_i = \frac{1}{1-i^2\lambda^2} \; and \; \lambda = \frac{2\pi v/L}{\sqrt{k_{12}/m_2}}$$

Equations (2) and (5) may be resolved in terms of v (velocity of the train) and L (mast pitch) using computers. In the simplified case of c_{12}=0, we do not even really need to use a computer.

For v=200 km/h and L=63m, we get

$$p = \frac{2\pi v}{L} = 5.54 \;\; rad/s$$

and

$$x_1 = 0.086 - 0.0124\cos pt + 0.0014\cos 2pt + 0.0008\cos 3pt(m)$$

$$x_2 = 0.1045 - 0.0117\cos pt + 0.0011\cos 2pt + 0.0004\cos 3pt(m)$$

$$F = 70 + 10.66\cos pt - 0.74\cos 2pt(N)$$

This would mean (given that it truly represented reality) that

F_{max}=81.4 N
F_{min}=58.6 N

At this speed the effect of the wind would be $F_w=0.0008v^2=32$ N
(this formula considers v in km/h)

But this value cannot be added to those obtained above because the system of equations (2) is non-linear and the implicit form of the equation (6) is a consequence of this non-linearity. In this case we could take the new value of 70+32 N instead of 70 N and start to resolve the system of equations again, but in our case it serves only to evaluate the coherence of the model we propose and push us on to try to determine the values for the parameters m_c, m_2, k_m, k_0 and c_{12} which are closer to reality. Later we may use the computer to resolve the problem in all its complexity.

2.4 Conclusions

As we stated before, these results have no real significance but help us to conclude the following:

- One important source of disturbance in the dynamic pantograph - catenary system is the variation in the spring rate of the OHEC along a journey

- The system is auto-excited with a frequency which is totally dependant upon the speed of the train and the mast pitch.

- The more uniform the spring rate of the OHEC, the smaller the variation in the contact force along the journey.

- The pantograph panhead must be dampened since it is practically impossible to avoid resonance speeds. In the simplified case which we have resolved, the resonance speed for L=63 m is 167 km/h.

- The theoretical results obtained by computer regarding the non-simplified system and including the aerodynamic effects of the wind, must be compared with practical tests under real conditions.
- If these mathematical formulae can be proven valid, we can then go on to optimise some of the pantograph parameters such as the spring and damping rates of the panhead suspension, taking into that account the panhead and pantograph masses (m_1 and m_2) do not leave a great deal of leeway.

3 - EXPERIMENTAL EVALUATION OF CONTACT QUALITY

3.1 Characterisation of contact quality

There is no unanimity about the characterisation of contact quality between the panhead carbon strip and the OHEC.

SNCF considers that the is measured by the number, duration and intensity of the sparks while DB bases this quality on the minimum contact force under running conditions.
Portuguese Railways currently uses a control by a videocamera which is installed in a specially adapted wagon which is towed behind the locomotive. The intensity, duration and number of sparks is recorded on the video and information about the places where anomalies exist is recorded on the sound track so that the catenary can later be repaired or substituted.

3.2 The evaluation method that we propose

We believe that the contact force is naturally more quantifiable and that it will give more information, specifically regarding the peaks of maximum force, which, while not causing sparks, does lead to exaggerated wear.

As you know, it is almost impossible to mount loading sensors between the zigzagging OHEC and the carbon strips. What we intend to do, therefore, is to measure this force indirectly, taking into account Newton's law.

The load sensors will be mounted at the extremes of the panhead and its elastic supports and miniature accelerometers will be mounted under the central part of the carbon strip support bars. The contact force will be equal to the sum of the force under the panhead and the inertia force of the panhead.

There is, however, another problem due to the electromagnetic field surrounding the panhead, quite apart from the 25 kV potential difference between the metallic parts of the pantograph and the carriage roof. We believe we can overcome this problem by transmitting the signals by fibre optic cables from the point of measurement to the instruments, which are mounted inside a wagon towed behind the locomotive.

We are currently looking for reliable and economic equipment both to conduct these measurements and to measure the height of the OHEC so as to determine the respective spring rate.

We think that we will then be in conditions to:

- evaluate the quality of the catenary with a standard pantograph which is to be defined;
- evaluate the quality of the pantograph on a standard stretch of catenary.

The pantographs which will be tested have been chosen from those proposed by the suppliers, before confirming the respective supplies, and also those which already exist in Portuguese Railways.

3.3 Equipment for evaluating the dynamic characteristics of repaired pantographs

The pantographs in Portuguese Railways are all of the same origin although, as we stated before, the more recent models have different dynamic characteristics, which make them more adequate for high speeds. These differences, however, are essentially due to the lighter weight of components, which are important for the dynamic behaviour.

They all have elastic suspension as shown in figure 2.

The respective spring rates and damping rates are highly dependant upon:

- the angles the arms were mounted at;
- the quality of the rubber parts

The angle that the arms were mounted at is also important so as to equally divide the contact force between the two carbon strips.

However, with intense use and some shocks caused by minor accidents, these angles may be successively altered causing the dynamic behaviour to change over time giving rise to a deterioration not only in the angles, but also in the rubbers which age with time.

We have conducted studies to characterise the influence of the parameters of tuning the elastic suspension of the panhead, and we designed an apparatus for measure the torsion spring rate and the torsion damping rate of the elastic suspension of the panhead, specifically those that were not originally supplied. We have thus tried that the pantographs repaired in the Portuguese Railway workshops, either in the case of accidents or due to intense use, recover the dynamic characteristics that they had when they were originally supplied.

4- SOME OF THE PHYSICAL ACCIDENTS AND THEIR RESPECTIVE CAUSES

We are referring here to accidents which had a purely mechanical origin but within this group we have excluded those caused by acts of vandalism. We have already investigated a significant number of accidents caused by mechanical failure, most of which were due to the fracture of the pantograph components.

In some of the accidents, the damaged pantographs caught the OHEC destroying long sections.

The destroyed OHEC then damaged the pantographs of the next passing trains.

The following are examples of typical fractures:

Fractures in the curved areas of the tubes of panhead (pantograph horns)
Fractures in the supporting bars

Our conviction of these fractures is:

A - Panhead Horns

The material shown in the maker's design is St35ϕ20DIN2391.
According to the norm: the tubes may be made cold drawn or cold rolled and may be supplied normalised, hard-drawn, soft-drawn or annealed, they may be of killed or rimmed steel, the chemical composition at casting is $C \leq 0.18\%$, $P \leq 0.05\%$, $S \leq 0.05\%$. In rimmed steel, these values may be up to 20% greater. In the conditions of supply, the annealed or normalised steels can be welded.

These specifications are incomplete since they do not refer to the conditions of supply, and therefore do not assure the use of the materials which are adequate for welding.

Even more serious is the fact that it may be rimmed steel.

If so we have two areas of weakness (brittleness).

The first will occur near where it is welded to the rest of the panhead, specially if the tube had been supplied cold-drawn. Actually the effect of the thermal cycle of welding on rimmed steel which had previously been strain hardened leads to an accelerated ageing resulting in the steel becoming more brittle.

The second will occur in the curved area of the tube. In fact, after hardening by cold plastic deformation and whenever galvanised, the thermal cycle will cause an accelerated ageing resulting in brittleness.

This second cause may have been at the base of the fractures we observed in the curved areas of the tubes of panhead horns.

We mustn't forget that the brittleness is more serious since the panhead horns are subject to conditions of fatigue.

B - Support Bars

This component works as a torsion bar whenever the panhead is being raised or lowered.
Fractures in the support bars have been one of the frequent causes of physical accidents due to mechanical origin which have occurred with pantographs.

In most cases, we have observed that these fractures begin in one of the two ends at the transition zone where the bar changes from 9 to 12 mm in diameter.

If we look at the results of the analysis of a fractured support bar we can see the following:

The inner-corner radii (radius) at the transition diameter at the two ends were measured and both had the same value of 0.4 mm.

However, as is known, there is a stress concentration at the transition diameters in the factor for which is K which is higher when the inner corner radii are smaller. So, the maximum stress at this point is $\tau_{máx}=K\tau$, where τ is the shearing stress which occurs in the smooth area of the narrowest part (9 mm).

For a torsion load, K is:

$$K = 1 + \frac{1}{\sqrt{\frac{2Ar}{d_2 - d_1} + \frac{2Br}{d_1}\left(1 + \frac{2r}{d_1}\right)^2 + C\left(\frac{2r}{d_2 - d_1}\right)^n \frac{d_1}{d_2}}}$$

where d_1 and d_2 , are the diameters (9 and 12 mm), r is the inner radius (0.4 mm) and A,B,C and n are coefficients which we can obtain from specialist texts.

By substituting these values we obtain the value of 1.655 for K. Note that K will tend towards the infinite when r tends towards 0. The greater the notch toughness and the local plastic deformation capacity at the inner radii, the less serious the stress concentration since the radius r could increase due to plastic deformation.

This is particularly true for static loads but the support bar is subject to dynamic loads. Therefore if in consequence of stress concentration the fatigue limit is exceeded, it will rupture after a certain number of cycles, starting precisely at the inner corner which should be explain the fracture we observed.

In the case we have just studied, it would seem that the inner radius could be increased to r=1.5mm which would reduce the stress concentration factor value to K=1.29.

5 – CONCLUSIONS

We have confirmed that the dynamic behaviour of the pantograph cannot be studied independently from the catenary. We have presented a model which lets us come to some conclusions regarding the non-uniform spring rate of the OHEC which disturbs the pantograph-catenary elastic system.

The study will now go on to refine the parameters definition and resolve mathematical equations of the more complex model.

During the work, we tried to found parameters for tuning the pantographs so that whenever they have to be repaired in the maintenance workshops, their dynamic behaviour is the same as when they were new.

Lastly, we analysed accidents which were caused by mechanical failure. We concluded that in some cases this was due to design faults while in others, incorrect materials were used.

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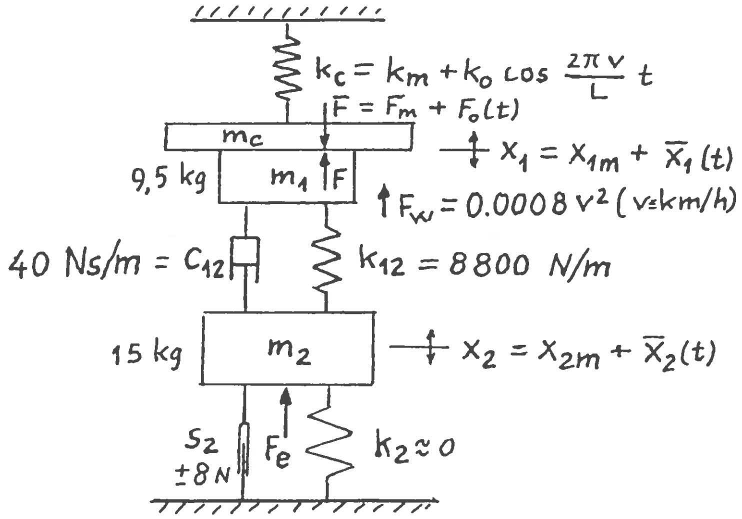
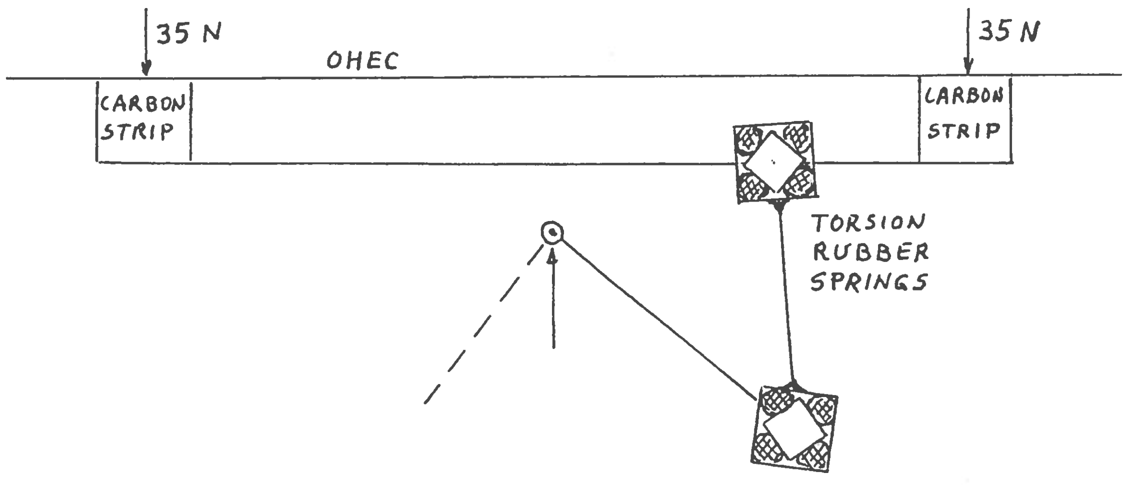


$k_c = k_m + k_o \cos \frac{2\pi v}{L} t$
$F = F_m + F_o(t)$
m_c
$x_1 = x_{1m} + \bar{x}_1(t)$
9,5 kg
m_1
F
$F_w = 0.0008 v^2$ (v=km/h)
40 Ns/m = C_{12}
k_{12} = 8800 N/m
15 kg
m_2
$x_2 = x_{2m} + \bar{x}_2(t)$
S_2
±8 N
F_e
$k_2 \approx 0$

Fig. 1



35 N
35 N
OHEC
CARBON STRIP
CARBON STRIP
TORSION RUBBER SPRINGS

Fig. 2