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Pantograph-catenary Dynamic Interaction for a Overhead Line Supported by Noise Barrier

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Abstract

Subject of the paper is a particular configuration of overhead line, in which noise barrier structure is used as supports of the catenary instead of standard poles. This configuration is foreseen in case the noise barrier position is in conflict with the poles location. If the catenary is supported by the noise barrier, the motion that the latter undergo due to wave pressure associated to train transit is transmitted to the overhead line, so that potentially it influences the interaction between the catenary itself and the pantograph of the passing train. The paper focuses on the influence of such peculiar configuration on the quality of the current collection of high speed pantograph, for single and double current collection. The study has been carried out first with an experimental investigation on the pressure distribution on noise barrier, both in wind tunnel and with in-field tests. Subsequently a numerical analysis of the dynamics of the barrier subjected to the wave pressure due to train transit has been carried out, and the output of such analysis has been used as input data for the simulation of the pantograph-dynamic interaction at different speeds and with front or rear pantograph in operation. Consideration of structural modifications was then highlighted, in order to reduce the influence on the contact loss percentage.

Key words: Pantograph-catenary interaction, noise barrier dynamics

1. Introduction

Train transportation has several advantages on motorway transportation from the point of view of environmental impact, especially in terms of CO₂ emission, accident reduction use of land, and time travel reduction [1]. Although with a lower impact, even rail transportation is involved in some item from the environmental point of view, between these the air borne noise can be of relevance when considering high speed trains.

For this reason noise barrier for the reduction of environmental noise can be necessary under required circumstances. As the necessary height of the noise barrier increases, its encumbrances increases too, possibly conflicting with the installation of the poles of the overhead contact line (OCL). As a solution it is conceivable to use the noise barrier itself as a support of the suspension of the catenary, instead of the usual poles. With this configuration, the wave pressure related to train transit causes a dynamic forcing on the noise barrier, whose motion, in turn, is transmitted to the OCL through the suspensions, so potentially influencing the quality of the current collection.

Main aim of the paper is to investigate how the motion of the noise barrier influences the quality of the current collection, at different speeds and pantograph location on the train. The work has been developed through a combined use of experimental tests and numerical simulation.

As a first step the characteristics of the wave pressure related to train transit has been experimentally defined by means of field tests and wind tunnel tests. In the former, pressure has been measured in two sections of the noise barrier during train transit, in order to obtain the pressure dependence on time, i.e., on train position. As for the latter, a reduced scale model of the noise barrier with a train located in the middle, has been tested, simulating the relative flow speed between noise barrier and train by means of the flow speed of the wind tunnel. Fitting the barrier model with several pressure taps, the spatial distribution of
the wave pressure has been so defined. It has been also possible to verify that time pressure wave and spatial pressure distribution wave are correlated through train speed. Normalized pressure time-space expression have been then obtained, allowing the definition of the loads on the noise barrier for different train speeds.

In a second step, a detailed model of a portion of the noise barrier has been set up by means of finite elements, and the responses of the noise barrier to the load pressure originated by train transit has been calculated in time domain through numerical integration.

Finally, the motion of the noise barrier in correspondence of the suspension point of the overhead contact line has been fed into a simulation program for the pantograph catenary dynamic interaction, so taking into account simultaneously the direct effect of the pantograph contact force, and the motion of the catenary induced by noise barrier motion.

Several scenarios have been simulated, varying train speed and considering two pantograph location on the train (i.e. placed on the head locomotive and on the trailing one), in order to verify if deterioration of the quality of the contact wire occurs for some conditions.

The paper is organized through the following points:

- overview of the solution of OCL supported by noise barrier;
- main result from wind tunnel tests and filed tests on noise barrier;
- model of the noise barrier;
- response of noise barrier to the wave pressure caused by train transit;
- simulation of pantograph-catenary dynamic interaction considering wave pressure effect on noise barrier;
- main conclusions.

2. Overview on Noise Barrier – OCL Configuration

In order to reduce the direct noise impact on surrounding environment, noise barrier can be placed along railway lines, with different heights according to the local situation and requirement for noise reduction. When the line is built in an area where there are space limitations and noise reduction requirement are relevant, it is necessary to get a compromise between noise barrier efficiency and available space for its allocation. The barrier is composed of three main elements, as shown in see Fig. 1 (right):

- a reinforced concrete support on its foundation;
- a steel structure for supporting the barrier and the suspension of the OCL, where appropriate;
- the barrier panels.

The barrier has a modular composition, being each module 4m long, which not necessarily coincides with the span length, generally subjected to variations in the order of 1m or more. The level of noise reduction depends also on barriers’ height, if the required height of the noise barrier exceeds 4m, its structure interferes with the structure of the pole supporting the overhead line (OCL).

A possible solution is to eliminate the standard pole, and to connect the suspension of the OCL directly to the supporting structure of the noise barrier. With this solution the full modularity of the barrier can be maintained, independently on the span length, i.e. on poles location.

3. Field and Wind Tunnel Tests on Noise Barrier

In order to define the pressure distribution on the noise barrier related to train transit, a combination of the results of field test and wind tunnel tests has been adopted. Field tests allowed to define the time history of the pressure for the case of a 4m height noise barrier, with the passage of a ETR500 train. Then the same condition has been reproduced in a reduced scale for wind tunnel (WT) testing.

Having reproduced the same pattern of the pressure wave, it was then possible to test also the maximum height of the noise barrier, extending the result obtained for the lower height. Once the pressure distribution along the barrier main axis and along its height was obtained, this allowed to define the dynamic pressure loads on the barrier, in order to simulate its dynamic response.

3.1 Field tests

The set-up of the field test consisted in several pressure measurements on the noise barrier, at two heights. It can be observed (Fig. 2) that the wave pressure pattern is the same along the barrier, so that a position difference corre-
The waveform related to the transit of the head (overpressure followed by an under pressure) and the tail of the train are clearly visible.

### 3.2 Wind tunnel tests

Wind tunnel test procedure is based on the principle of reproducing the relative flow between air and train. In the real condition (see Fig. 3) the train is moving and the flow speed relative to the train is opposite to train speed, while air and barrier are obviously at rest. As well known, a pressure variation is caused by the motion of the front of the train [2], and to the confined flow between train and barrier. In the WT test, the incident flow represent the flow speed relative to the train, and the confined flow between train and barrier. In order to have full equivalence, the barrier should be moving too, but considering the approximation of an infinitely long barrier, the geometry of the confined flow and its relative speed between with respect to the train does not change, and as a consequence the pressure distribution remains the same. The approximation is valid if the pressure effects are predominant over the viscous flow effect, as for the considered case. The control on the level of approximation of such hypothesis is based on the comparison between the time history of the pressure on the field test, and the space distribution in the WT tests, as will be demonstrated further on. The set-up of the wind tunnel (see Fig. 4) consists of a 1:10 reduced scale model. The noise barrier is fitted with an array of pressure taps close to the train head.

As previously mentioned, a difference in space position correspond to a time shift in time domain. If this condition is verified, the time history registered during the field test can be superposed to the space distribution of the pressure measurement in wind tunnel, according to the follow-
ing relationship:

\[ \Delta t = \frac{\lambda \Delta x}{V} \]  

(1)

Where \( \Delta t \) is the time step corresponding to a space step \( \Delta x \), \( \lambda \) is the scale of the model and \( V \) is train speed. For the direct comparison, the values the pressure are scaled through the pressure coefficient \( C_p \):

\[ C_p = \frac{2p}{\rho V^2} \]  

(2)

Where \( p \) is the measured pressure, \( \rho \) is the air density, and \( V \) represents train speed, and the flow speed, in the case of the wind tunnel test. Once the condition (1) has been verified, it is now possible to use the results of the wind tunnel tests on a model of the 10 m height barrier (Fig. 6) and use the results of the pressure taps, in terms of pressure coefficients \( C_p \) (as in eq. 2), to extrapolate the pressure time history in full scale from, as reported in for different levels from top level of the rail. The shape of pressure distribution is typical, with a increase just in front of train head, and a subsequent decrease just behind (see f.i. [3]).

### Table 1. first natural frequencies of the barriers series under dry and wet conditions

<table>
<thead>
<tr>
<th>Mode type</th>
<th>Dry condition</th>
<th>Wet condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st}) flex.</td>
<td>5.492 Hz</td>
<td>4.497 Hz</td>
</tr>
<tr>
<td>2(^{nd}) flex</td>
<td>5.499 Hz</td>
<td>4.050 Hz</td>
</tr>
<tr>
<td>3(^{rd}) flex.</td>
<td>5.505 Hz</td>
<td>4.056 Hz</td>
</tr>
</tbody>
</table>

4. Simulation of Noise Barrier Response to Wave Pressure

#### 4.1 Noise barrier model

A finite element model has been built in order to reproduce the structure. In particular (see Fig. 8) plate elements have been used for the concrete base support, beam elements for the composed main beam, while the barrier panels have been considered simply as mass elements, disposed on the main beam, without any structural capability. The mass related to the panels has a distributed mass of 50 kg/m\(^2\), in dry condition. Being the panel porous, they can absorb rain water, reaching a maximum of 150 kg/m\(^2\) under complete wet condition.

A complete support series is then assembled (see Fig. 9), where a 120 m long structure is shown, All the supporting beams of each module are connected through a longitudinal beam, giving a slight coupling for the flexural
motion. As a result, the frequencies of the first modes of the complete structure are all grouped around the value of the first flexural mode of the single module. As an example the mode shape of the first three modes is reported in Fig. 10, for dry condition.

4.2 Simulated response of the noise barrier

Once the model of the noise barrier is defined, the dynamic response to wave pressure can be calculated, having defined the pressure time history corresponding to each speed, as explained in §3. The finite element model is integrated in the time domain: Fig. 11 and Fig. 12 show the time history of the nodal points representative of the motion of the connecting point of the suspension (see Fig. 13).

The time history pattern show the response to the first double pulse of the pressure related to the head of the train, a decay related to the structural damping of the noise barrier structure, followed by the response to the final double pulse, related to the passage of the tail of the train. The effect of the latter is more visible in the wet condition.
5. Model of Pantograph-catenary Dynamic Interaction with Noise Barrier

5.1 General procedure

Several mathematical models of pantograph-catenary dynamic interaction have been proposed and implemented in numerical codes. The literature on this topic is quite large, ranging from semi-analytical model like [4], to partial differential equations for the catenary and differential-algebraic equations for the pantograph [5], special modal approach [6,7], finite element [8,9] including non linearity of the droppers [10]. In this paragraph the main features of the modal superposition approach: the motion of each collector is expressed as a combination of its modal shapes when considering the force-displacement relationship obtained from laboratory tests [9]. A finite element approach has been adopted for overhead line (OCL) schematisation.

The droppers are included as non-linear elements, considering the force-displacement relationship obtained from laboratory tests [9].

The pantograph is represented by means of a non-linear lumped mass system. The values of the lumped parameters in the pantograph model are obtained by an identification process based on the measured frequency response (FRF) of the pantograph.

In order to study the effects of high frequency interaction with the overhead equipment, the model also includes the bending deformability of the collectors by a modal superposition approach: the motion of each collector is expressed as a combination of its modal shapes when considered as a free body, thereby introducing a vector of modal coordinates. For each collector, the two rigid modes (vertical and roll motion) and the first bending modes of the free collectors can be included in the analysis. The vector $\mathbf{q}_p$, collecting the pantograph coordinates is therefore as follows:

$$
\mathbf{q}_p = \{ \mathbf{z}_p \mathbf{T} \mathbf{z}_m \mathbf{T} \mathbf{z}_r \mathbf{T} \}
$$

(3)

Where $\mathbf{z}_p \mathbf{T}$ is the vector of the pantograph degrees of freedom of the articulated frame, $\mathbf{z}_m \mathbf{T}$ and $\mathbf{z}_r \mathbf{T}$ are the sub-vectors collecting the modal coordinates of the two collector heads. The interaction between the collectors of the pantograph and the contact wire of the overhead line is based on the penalty method considering a contact stiffness and the related damping [11]. As a consequence, the contact force is a function of the motion both of the contact wire and of the two collectors in correspondence of the location of the contact point. The motion of the contact wire in correspondence of the contact point is calculated by means of the shape function of the finite element that contains the contact point, while the irregularity of the vertical level of the contact wire is superposed to the motion of the contact wire. The motion of the collector in correspondence of each contact point is calculated through the modal superposition of the modes of each collector, considering the position of the contact point according to the stagger of the contact wire. The equations of motion of the two subsystems are integrated in the time domain, iterating at each time step:

$$
\begin{align*}
[M_p] \ddot{x}_p + [R_p] \dot{x}_p + [K_p] x_p &= E_c (x_c) + E_p (x_p, \dot{x}_p, \dot{x}_c, t) \\
[M_p] \ddot{x}_c + [R_p] \dot{x}_c + [K_p] x_c &= E_p (x_p, \dot{x}_p, \dot{x}_c, t)
\end{align*}
$$

(4)

where the subscript c refers to the catenary and the subscript p to the pantograph. On the right-hand side of each of the first two equations, the generalised terms due to the contact forces are also direct function of time, due to the presence of the irregularity of the contact wire. Finally, $E_c(x_c)$ accounts for the non linear effects of the droppers slackening.

5.2 Insertion of the motion of the noise barrier

In order to include the effect of the motion of the barrier in the standard procedure for the pantograph-catenary interaction, first the motion of the connecting points of the OCL to the suspension is derived from the motion of the barrier (see Fig. 13), considering the suspension frame as a rigid frame. Then the obtained motion is included as input on the eq. 1, adding a time dependant term $E_c(t)$ in the OCL equations:

$$
\begin{align*}
[M_p] \ddot{x}_p + [R_p] \dot{x}_p + [K_p] x_p &= E_c (x_c) + E_p (x_p, \dot{x}_p, \dot{x}_c, \dot{x}_c(t), t) \\
[M_p] \ddot{x}_c + [R_p] \dot{x}_c + [K_p] x_c &= E_p (x_p, \dot{x}_p, \dot{x}_c, \dot{x}_c(t), t)
\end{align*}
$$

(5)

The approach is based on the simplifying assumption that the motion of the OCL does not influence in a significant way the motion of the barrier, considering that the first frequency of the barrier (not less than 4 Hz) is four times higher than the first frequency of the catenary span (about 1Hz), and the modal mass of the barrier is much higher than the one of the OCL. As a consequence, the motion of the barrier is considered influencing the motion of the OCL, but not viceversa.

6. Results of Pantograph-catenary Simulation

6.1 Main data of the analysis

The application is done on the standard Italian high
speed catenary (C270), suitable for operating speed of 300 km/h (see Table 1). Span length is 60 m, droppers are at 6 and 6.5 m distance, being the first at 5.1 m from suspension. A scheme with 14span is considered for the simulation, barrier are inserted for a length of 240 m, from 360 m to 600 m.

Pantograph model reproduces the ATR95-25kV type, considering the kinematics of the suspension of each collector (Fig. 14 and Table 2). Simulations have been carried out at 200, 250 and 300 km/h, considering two conditions: when the front pantograph is raised, and when the rear pantograph is raised. The distance between front and rear pantograph locations is 205 m (d2 in Fig. 15). This has an impact on the effect of the noise barrier motion, as depicted in Fig. 15. For each section the time history of the wave pressure depends on the head train position, but the pantograph travels under the OCL according to its location on the train. Therefore there are different time delays between the application of the wave pressure front on each section of the noise barrier, and the arrival of the pantograph, according to the distance d1 (case of front pantograph raised), and d1+d2, in case of rear pantograph raised.

6.2 Results in standard configuration

The results of the simulation is presented first for the standard condition, i.e. without noise barrier. Contact force for the case of 300 km/h is reported in Fig. 16 for the single pantograph, in terms of spectrum and force vs. pantograph position, along the central five spans. When considering standard configuration it front or rear condition can not be distinguished. Spectral analysis shows contributions at the span passing frequency (at 1.38 Hz) and in correspondence of dropper passing frequency, in the 12÷15 Hz frequency range.

6.3 Results for the configuration with the OCL supported by the noise barrier

Fig. 17 shows the quality index $F_{m-3s}$ of the contact force of the front pantograph (filtered at 50 Hz) and of the rear pantograph, at 300 km/h only. It can be observed that the application of the motion of the noise barrier as supplementary input to the OCL equations, brings a general a deterioration of the quality of the current collection, especially at 300 km/h. For this speed
also the condition of the rear pantograph is analyzed. It can be seen that with dry barrier condition the quality index goes under the limit, being even negative. The observation of the statistical quantity alone is nevertheless not enough to judge the current collection, so also contact loss are considered. Contact loss percentage are judged from the simulation considering zero value of the contact force.

Going more into details, comparing Fig. 18 (simulation with noise barrier motion) with Fig. 16. (results in standard configuration) it can be observed that for the front pantograph (upper graph), the effect of the additional motion related to noise barrier is confined only under suspension, where a contact loss condition is found.

As for the condition when rear pantograph (lower graph) is raised, it can be seen a strong impact on the contact force, resulting in a heavily deteriorated condition.

The result can be interpreted with the help of the observation of the motion of the contact point of the pantograph reported in Fig. 19.

For the front pantograph raised configuration (upper graph) the shape of the trajectory is somehow amplified but not substantially changed, while when the train travels with rear pantograph raised (lower graph) there is a complete alteration for the case of dry barrier, justifying the relevant alteration of the contact force seen in Fig. 18.

In order to improve the observed condition and overcome the disadvantages found from simulation, it is then necessary to decrease the level of dynamic response of the noise barrier. This has been achieved through a modification of the connection of the supporting beam to the concrete base, since it was found that this connection originates most of the deformability. The modification of this connection, aimed at increasing its stiffness and consequently the natural frequencies of the flexural modes. In order to show the improvement with the structural modification of the connection of the supporting beam with the concrete base, Fig. 20 reports the contact loss percentage for the updated configuration, in comparison with the actual one: a drastic reduction of the contact loss percentage is found from the results of the simulation.
7. Conclusion

In the present paper the analysis of a peculiar configuration in which the OCL is suspended to noise barrier instead of the standard poles has been investigated. Aim of the investigation is to define the impact that the motion of the noise barrier, induced by the wave pressure related to train transit, transmitted to the OCL, has on the quality of the current collection. Reference pressure loads on the noise barrier has been obtained combining in line tests and wind tunnel tests on a reduced scale model. The combination of the experimental data and procedures and mathematical modeling of pantograph-catenary dynamic interaction allowed to identify potentially deteriorated condition. The results at 300 km/h suggested a modification of the noise barrier structure in order to decrease its level of dynamic response. The updated structure showed its capability in reducing the impact on the current collection quality.

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