COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

TRANSVERSAL VIBRATION CONTROL FOR CATENARY POLES ON A HIGH SPEED RAILWAY BRIDGE

C. Anicotte[1] and D. Botton[2]

[1] SNCF Engineering and Projects Direction
6 avenue François Mitterrand 93574 La Plaine Saint Denis, France
e-mail: celine.anicotte@sncf.fr

[2] RFF – Bourgogne Franche-Comté Regional Direction
22 rue de l'Arquebuse - 21078 Dijon cedex France
dominique.botton@rff.fr

Keywords: Catenary supports, resonance, railway bridge dynamics, finite elements modelling, vibration control, tuned-mass dampers

Abstract. *The study presented in this paper deals with the excessive transversal vibrations of the catenary poles located on the Savoureuse viaduct; a railway bridge on high speed line in France. This viaduct across the Savoureuse River opened in 2011 for commercial runs of high speed trains between Dijon and Mulhouse in France. During inspection visits, the maintenance agents on site detected that the catenary poles presented strong transversal vibrations perpendicular to the track axis. RFF and SNCF were then concerned for the integrity of the concrete boxes fastening the catenary poles and the stability of the catenary itself. A full study was carried out by SNCF to explain the phenomenon and to find the best solution to reduce these transversal vibrations.*

1 INTRODUCTION

The viaduct across the Savoureuse River is special bridge with 12 independent spans based on 2 abutments and 11 architecturally designed tetra-pod piers. The bridge deck is composed of two main lateral girders, transversal floorbeams and a filler beam slab resting on the floorbeams. Each span is bearing 2 catenary poles (HEA 240 girders) per track. The poles are located on the filler beam slab at approximately quarter-span on either side.

Figure 1: Aerial photograph of the Savoureuse viaduct

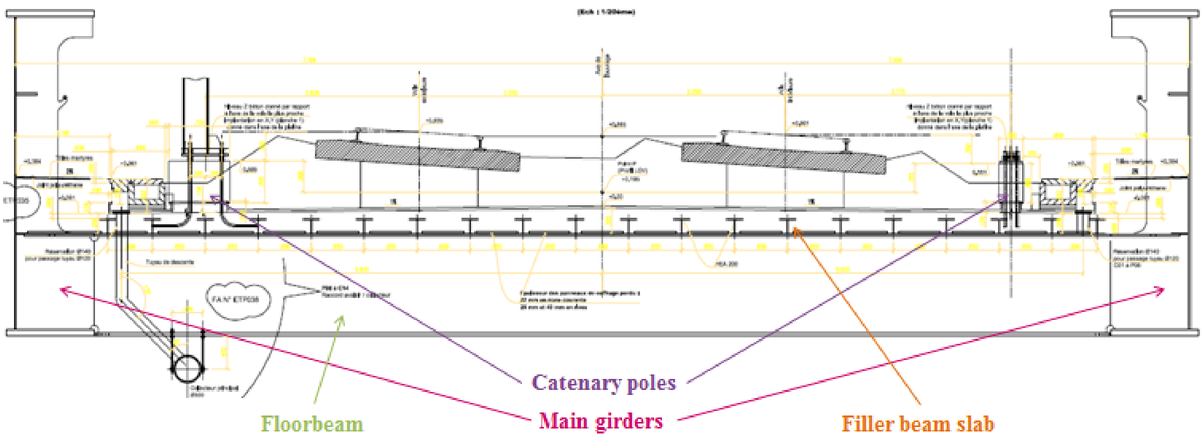

Figure 2: Cross section of the Savoureuse viaduct

During inspection visits, the maintenance agents on site detected that the catenary poles presented strong transversal vibrations perpendicular to the track axis. These vibrations occurred only when TGV trains were passing at 170 km/h to stop at a train station a few kilometres further; TGV trains running at full speed (320 km/h) did not create any important vibrations.

In order to fully explain the phenomenon and to find an adapted solution, it was decided to model the effect of trains passing on the bridge on the dynamic response of the catenary poles. To quantify exactly the transversal vibrations and to validate the model, dynamic measurements were carried out on the bridge and the catenary poles.

2 DYNAMIC MEASUREMENTS ON THE STRUCTURE

The dynamic measures consisted in setting accelerometers and displacement sensors on different points of the structure.

For the bridge, measures were made at the line opening in 2011 with accelerometers and displacement sensors at the middle of spans number 1, 10, 11 and 12. These measures were used to adjust the Finite Elements model of the bridge. The first eigenmode of longitudinal bending was found at 2.23Hz for 66m-long spans (between pier n°2 and pier n°12) and 2.62Hz for 66m-long spans (end spans).

For the catenary poles, transversal accelerometers were placed at the top of 3 poles on the same span of the viaduct. The amplitude of transversal displacement was obtained by integrating twice the acceleration signal.

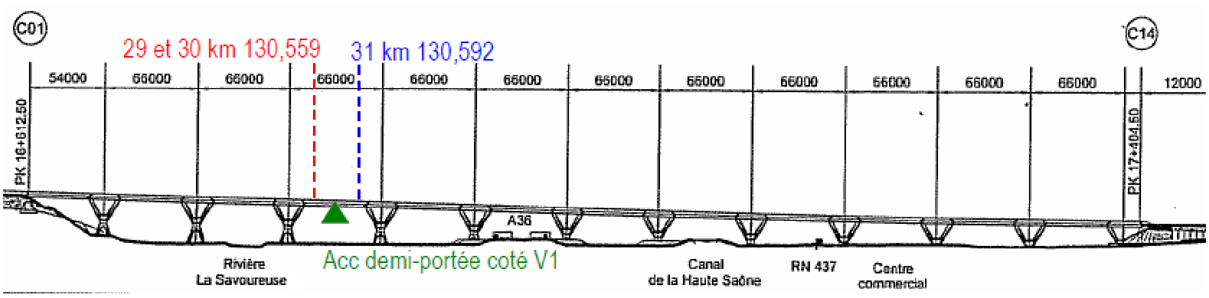

Figure 3: Location on the viaduct of the poles equipped with accelerometers

Figure 4: Fastening of the accelerometer on top of the catenary pole

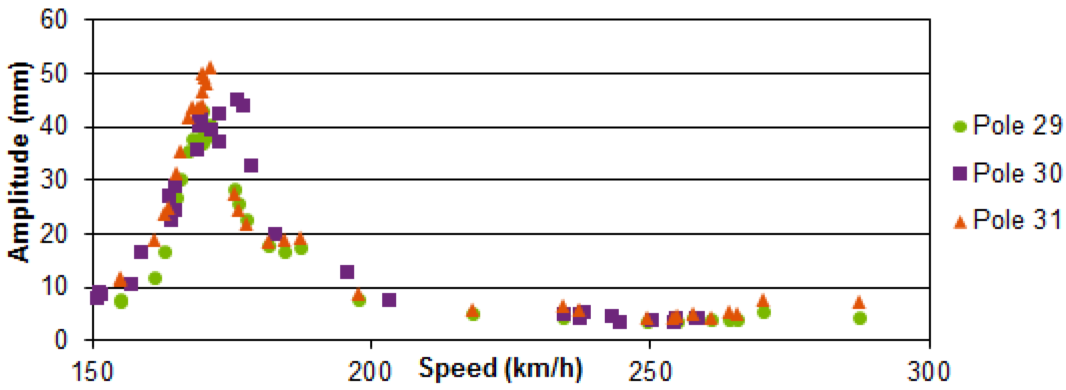

Figure 5: Results of measurement for the 3 equipped poles

These measurements on top of the catenary poles showed that the amplitude of transversal displacements reaches the maximum of 51mm on pole 31 for trains running at 170km/h. This form of curve is characteristic of a resonance phenomenon.

The main frequency measured on all the poles is comprised between 2.5 and 2.6 Hz, which corresponds exactly at the critical speed for TGV of 170 km/h (a bogie passing every 18.7m).

3 MODELLING OF THE STRUCTURE

3.1 Bridge model

To explain perfectly this resonance phenomenon and to find the best solution to reduce the vibration, a Finite Element model of the structure was created.

To reduce the calculation times, only the first three spans of the bridge were modelled and the results were extracted on the central span. The program ANSYS was used to create the model.

All the beams (Main girders, floorbeams, piers, etc.) were represented as BEAM188 elements and the filler beam slab as SHELL181 elements.

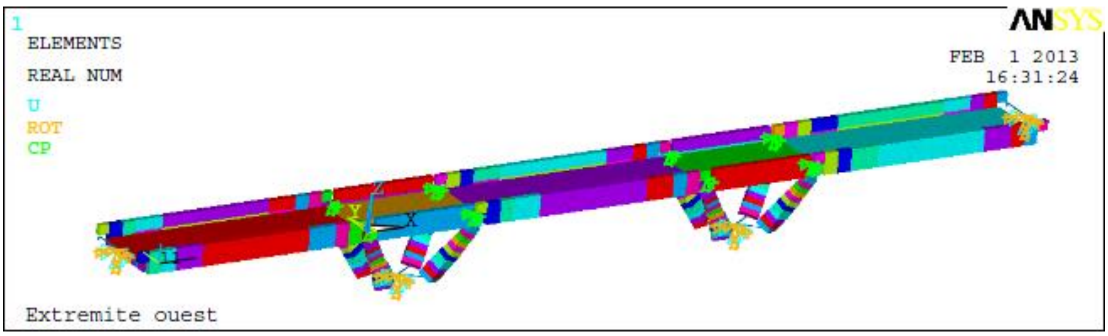

Figure 6: General view of the viaduct Finite Elements model

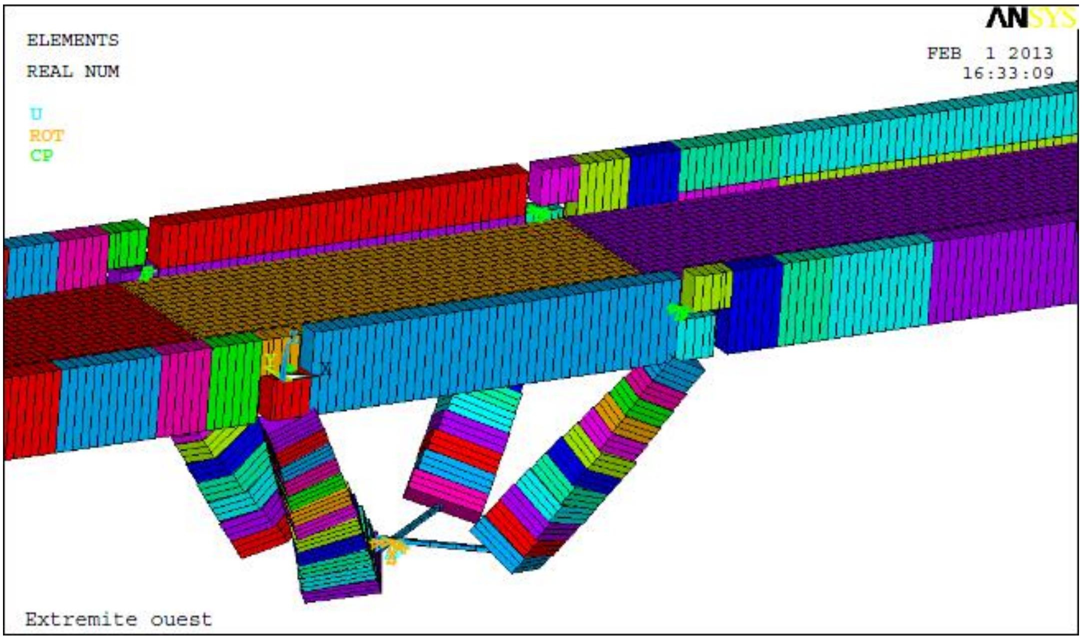

Figure 7: Zoom on the pier of the viaduct Finite Elements model

The young's modulus of the concrete was adjusted to 36GPa to get results as close as possible from the measurements.

The catenary poles were then added as simple beams on the viaduct taking into account the different masses of:

- The HEA 240 girder
- The concrete foundation in which is clamped the girder
- The earth wire
- The cantilever
- The line feeder and its support
- The messenger and contact wires

The transversal offsets of the cantilever, the line feeder and its support and the messenger and contact wires were respected in order to get the exact mass in rotation.

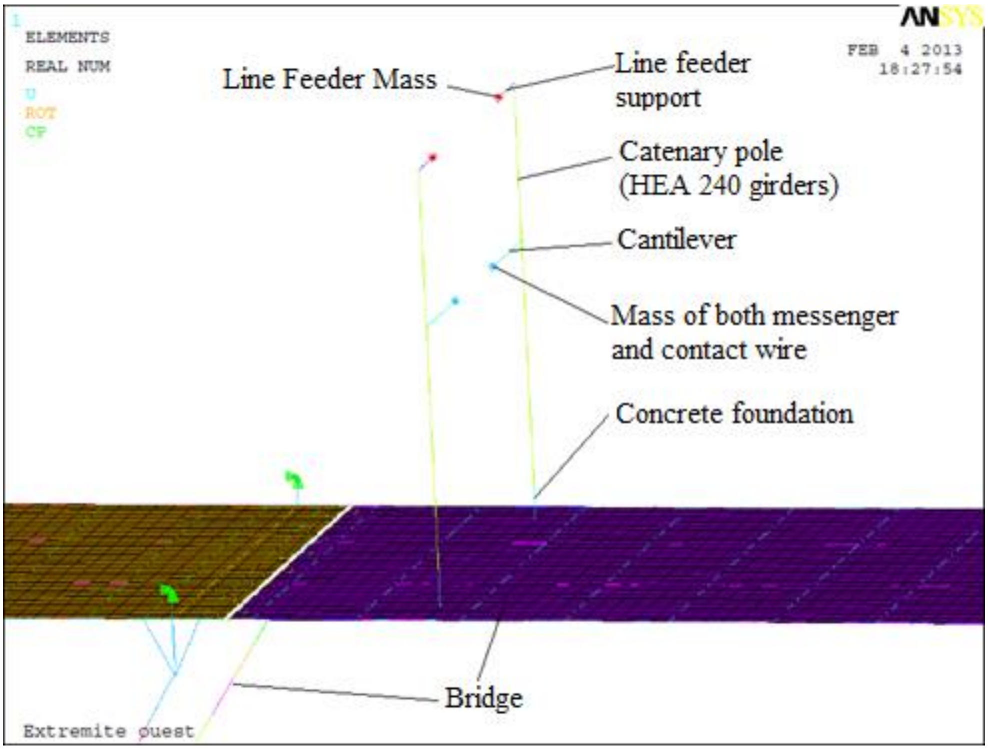

Figure 8: FE Modelling of the catenary poles on the viaduct

The first transversal bending eigenmode for the poles was calculated by Ansys at 2.19Hz (very close to the bridge first bending mode at 2.2Hz). This value is not exactly the value measured on the poles at 2.5Hz. Moreover, the dynamic response of the catenary poles obtained with this model was very far from the measured response. No resonance was highlight with the TGV at a running speed of 170 km/h, nor at 150 km/h (critical speed for TGV with bogies every 18.7m to excite a frequency of 2.2Hz). This model did not seem to represent well what happened really on the viaduct.

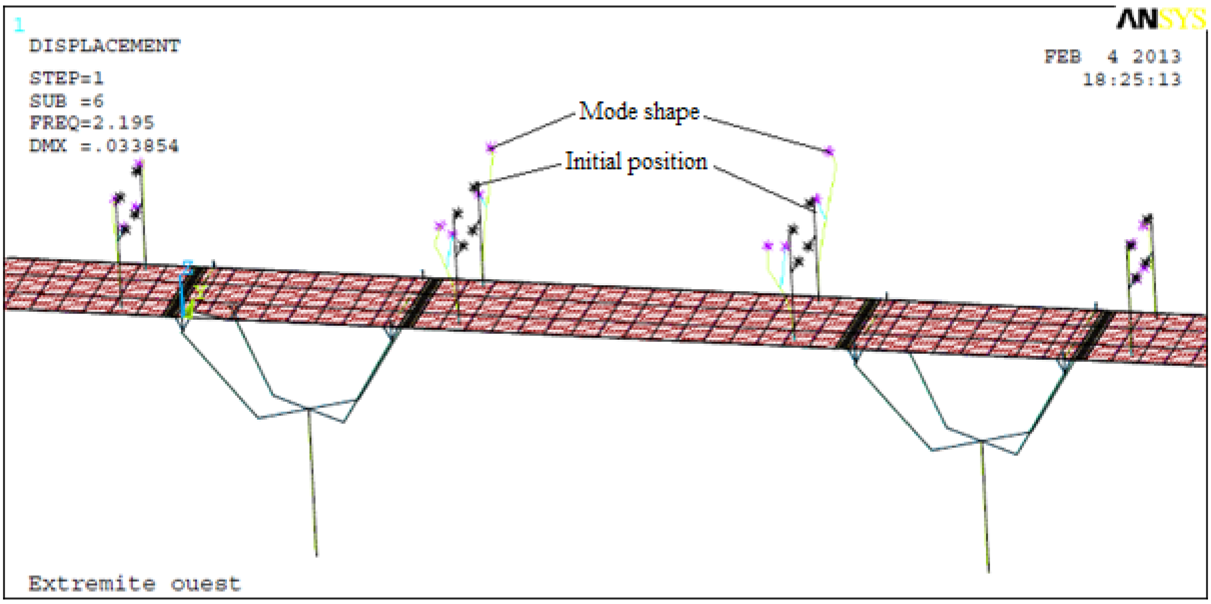

Figure 9: First bending mode of the catenary poles

A more detailed model of the poles seemed then needed to characterize the resonance phenomenon: the interaction between the wire and the poles is probably of great influence. The aspect of all the curves measured on the poles (see Figure 10 for example) validates this hypothesis as a beating phenomenon can be observed: the transversal vibration increases again after the train has left the bridge. These kinds of beats are usually observed in case of coupled systems.

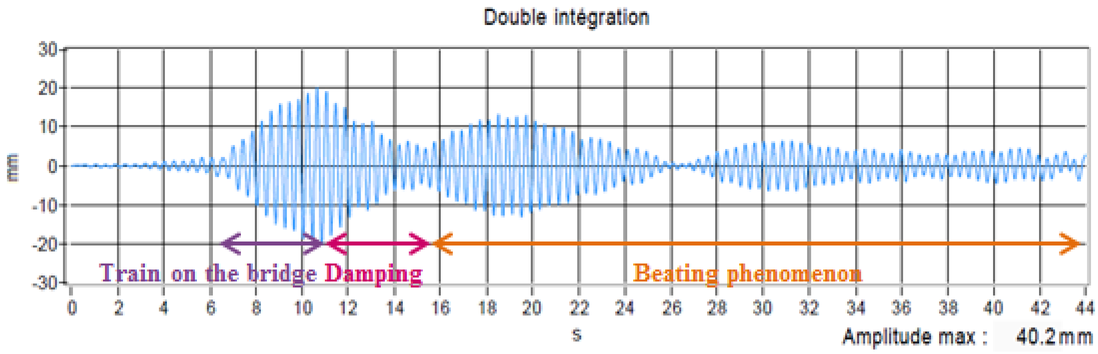

Figure 10: Example of transversal displacement obtained on top of the pole

3.2 Catenary pole model

The different wires (messenger, contact and line feeder) are coupled with the poles and create a coupling between all the poles. This system can be first approximated by a simple system with 2 oscillators as shown in the figure below.

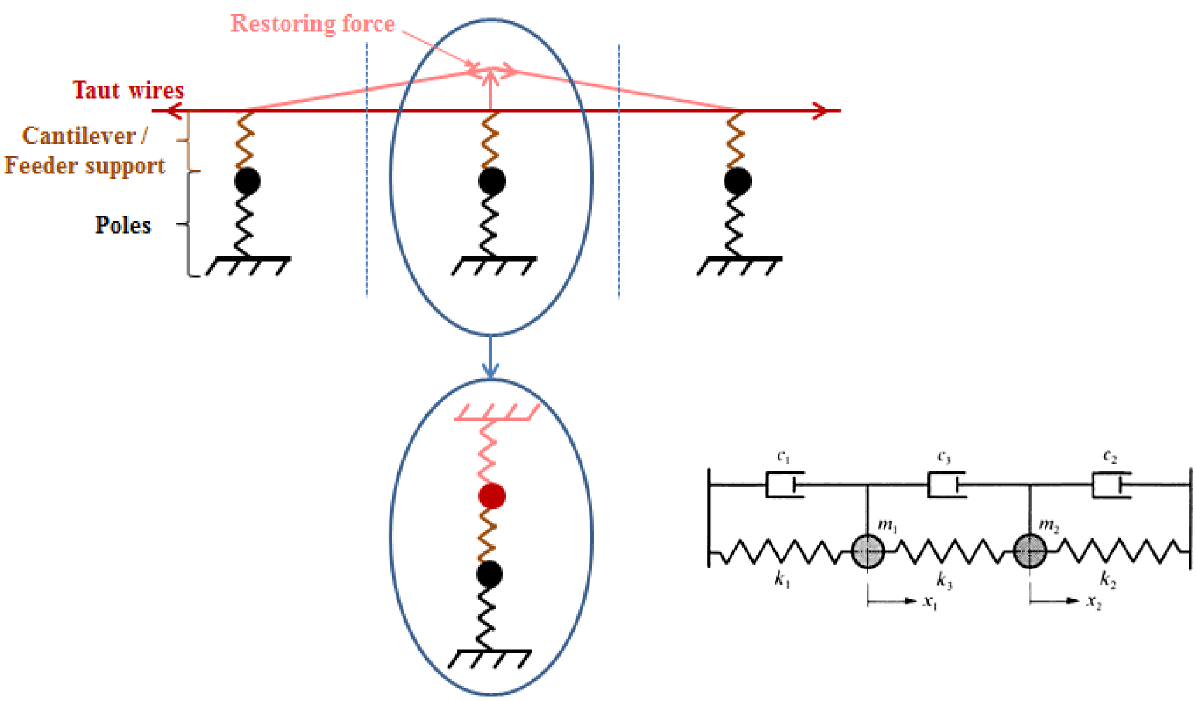

Figure 11: Catenary wires as 2-degrees of freedom oscillating system

Only the effect of the messenger and contact wire is first studied. The effect of the line feeder has then proven to be negligible as the connection to the pole is free to move transversally.

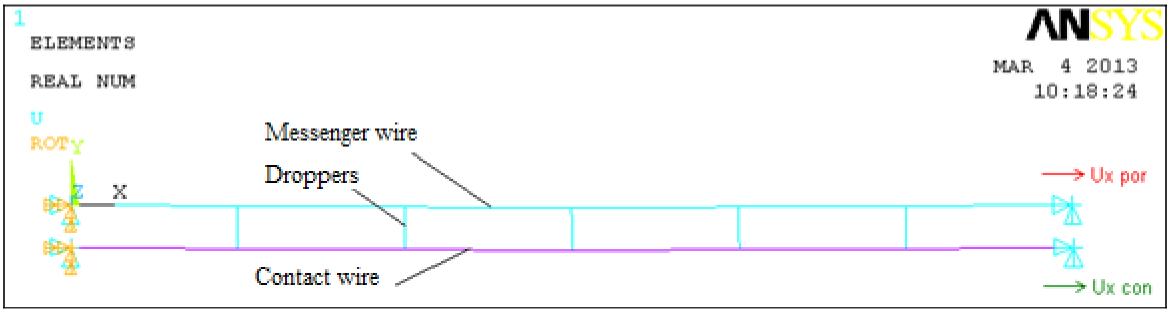

Figure 12: FE modelling of messenger and contact wire

To simplify the calculation with the different wires, it was shown by FE model that the effect of both messenger and contact wires linked by droppers was equivalent to one wire with both masses and initial tensions. By FE model, the first bending frequency was calculated transversally at 2.09Hz and vertically at 2.11Hz.

The frequency calculated analytically by the following equation for a taut wire is equal to 2.08Hz which is sufficiently close to the modelled values.

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \tag{1}$$

With L: the wire length
μ: the linear mass
T: the wire tension

Taking into account notations of Figure 11, the 2 frequencies of the coupled system are:

$$f_1 = \frac{\sqrt{\left|\frac{-B+\sqrt{B^2-4C}}{2}\right|}}{2\pi}$$
$$f_2 = \frac{\sqrt{\left|\frac{-B-\sqrt{B^2-4C}}{2}\right|}}{2\pi} \tag{2}$$

With

$$B = \frac{k_1+k_3}{m_1} + \frac{k_2+k_3}{m_2}$$
$$C = \frac{k_1k_2+k_2k_3+k_1k_3}{m_1 \times m_2} \tag{3}$$

Knowing that the frequency of the pole alone is 2.2Hz and its mass 710 kg, k_1 is calculated as $9.59\text{x}10^4$N/m; and k_2 is calculated equal to $1.11\text{x}10^4$N/m with the frequency of the wires equal to 2.08Hz and its mass to 80kg.

Finally, with the above equations, f_1 is calculated equal to 2.18Hz and f_2 to 2.52Hz with 2.52Hz corresponding to the vibration of the pole. This value is very close to the measured frequency.

The next step in the study was to know which force actually excites the pole to the resonance: vertical displacement or rotation of the bridge deck. A simple model of a pole with the characteristics defined above was made with Ansys (see Figure 13). In this model, the frequencies of 2.18Hz and 2.52Hz were found again. The vertical displacement and rotation of the bridge deck found at the foot of the pole are applied separately at the bottom of the model.

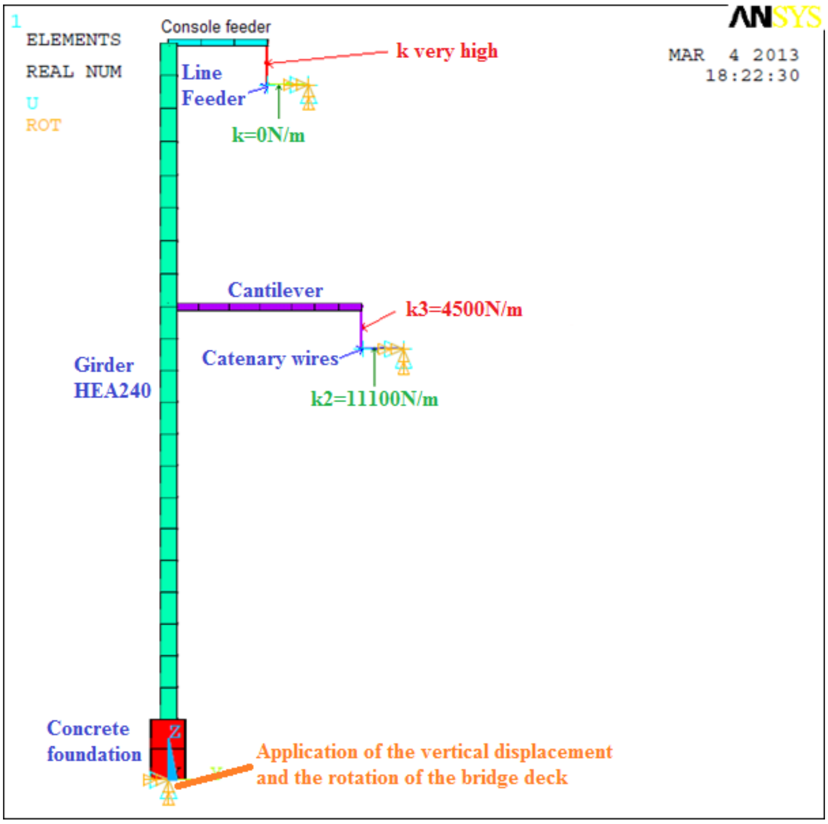

Figure 13: FE modelling of a catenary pole

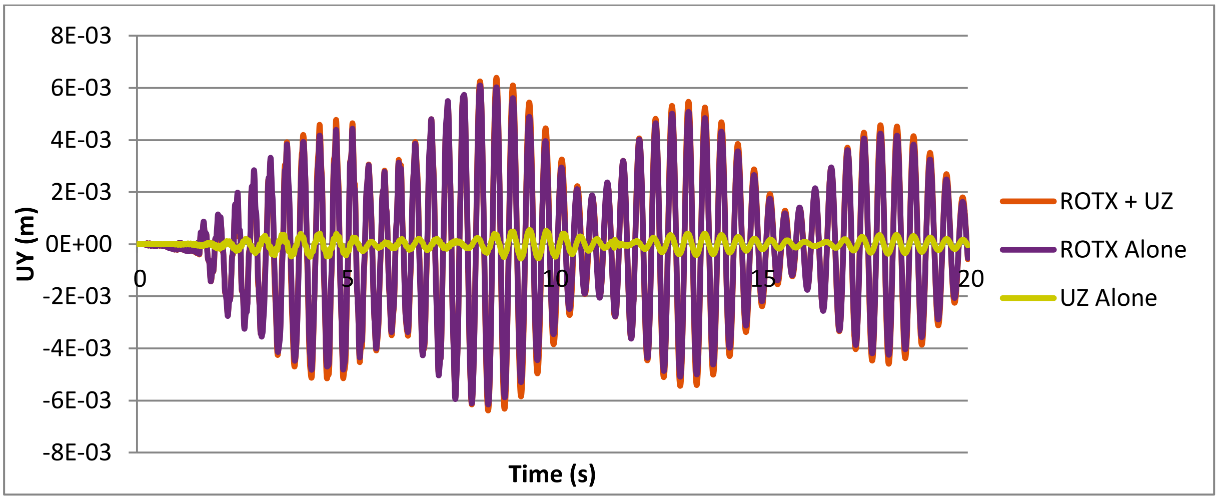

Figure 14: Comparison of transversal displacement on top of the pole under different excitations

With this test, it is clear that most of the resonance comes from the rotation of the bridge slab. This bridge composed of 2 very rigid main girders and a softer slab is more sensible to this type of transversal bending than reinforced concrete slab or bridges with the main girders below the slab.

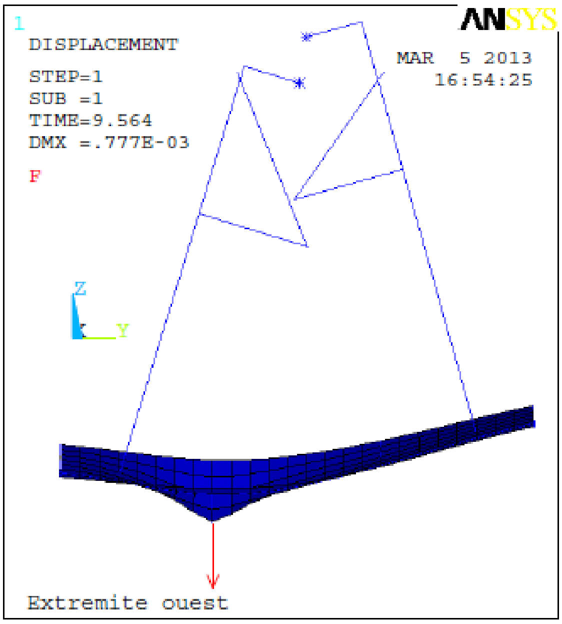

Figure 15: Transversal bending of the deck slab and rotation of the catenary pole when a TGV bogie is passing

Finally, the FE model representing the bridge and the poles was updated to take into account the previous investigations.

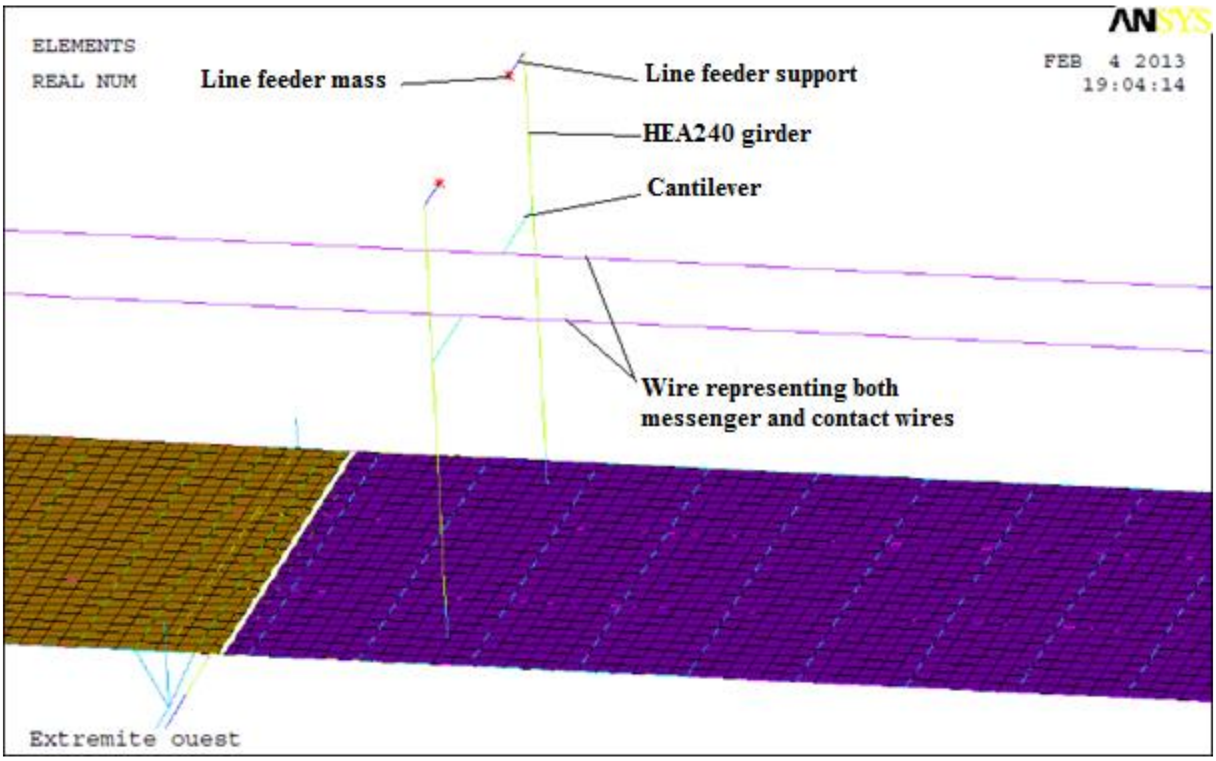

Figure 16: New FE model of the catenary poles on the bridge taking into account the interaction of the wires

The following figure shows that with this FE model, the results of calculations are quite close to the measurements. With this new model, the different solutions could be tested to check their efficiency.

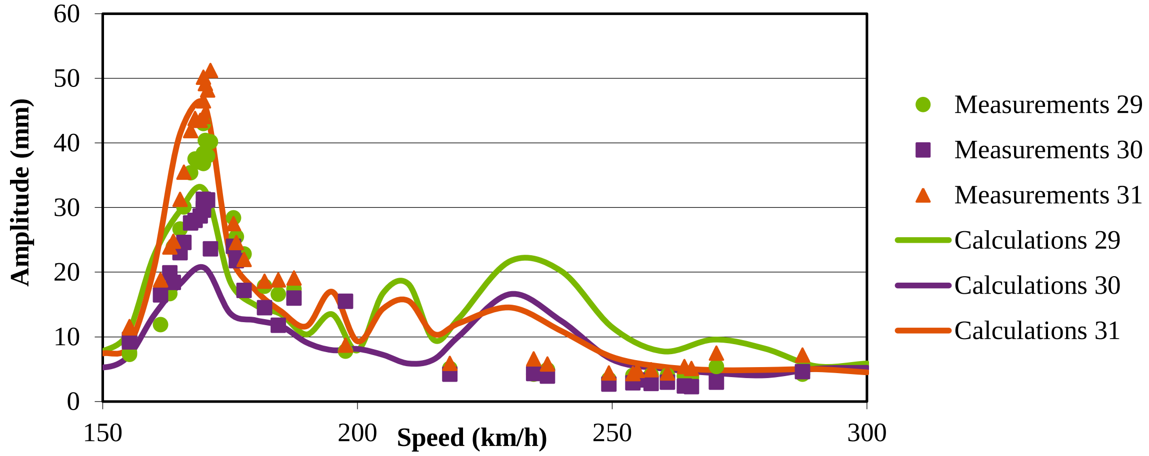

Figure 17: Comparison of the transversal displacement amplitude between calculations and measurements

4 PROPOSAL OF DIFFERENT SOLUTIONS

Different solutions were proposed by SNCF to solve this vibration problem:

- Replacement of the HEA 240 girders by HEA 300
- Setting of an additional crossbar linking the poles on each side of the tracks to create a portal frame effect
- Setting of Tuned Mass Dampers (TMD) on top of the poles

4.1 Replacement of the girders

The first idea submitted to solve this problem was to replace the HEA 240 girders by HEA 300 that are usually recommended by SNCF for high speed lines.

In the model shown in Figure 16, the characteristics of the beam representing the girders are then updated to those of HEA 300. The results of maximum amplitude of transversal displacement regarding the running speed of TGV are given in Figure 18.

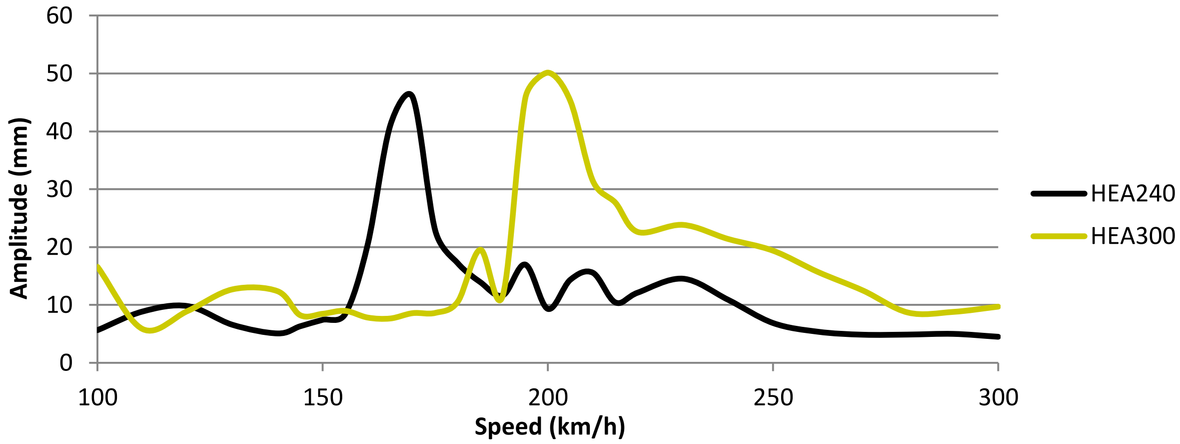

Figure 18: Comparison of the transversal displacement amplitude between HEA 240 and HEA 300

According to the previous figure, it is clear that replacing the girders is not an efficient solution as it offsets the resonance problem to a higher speed. The bending frequency of the catenary pole with a HEA 300 girder is 2.9Hz, corresponding to a critical speed for TGV of 200km/h. The new girder being stiffer, the response at the resonance is expected to be lower. However, the bridge deck rotation increases with the speed. The maximum amplitude obtained at resonance is therefore equal with HEA 300.

4.2 Setting of a crossbar

Another solution proposed by SNCF was to add a crossbar between the poles on each side of the tracks to create a portal frame effect. The position of this crossbar on the poles is very constrained by the isolation offsets to respect regarding the conductors.

Figure 19: Example of crossbar

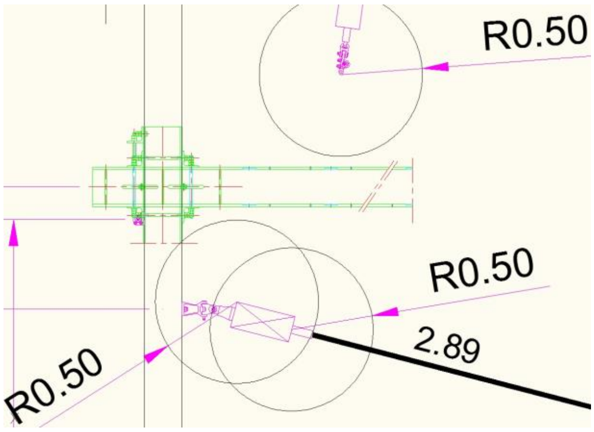

Figure 20: Isolation distances to respect

The crossbar was then modelled in Ansys at its determined position and the transversal response of the catenary poles was calculated with the TGV at different speeds. The first transversal bending frequency of the whole portal was calculated at 1.99Hz.

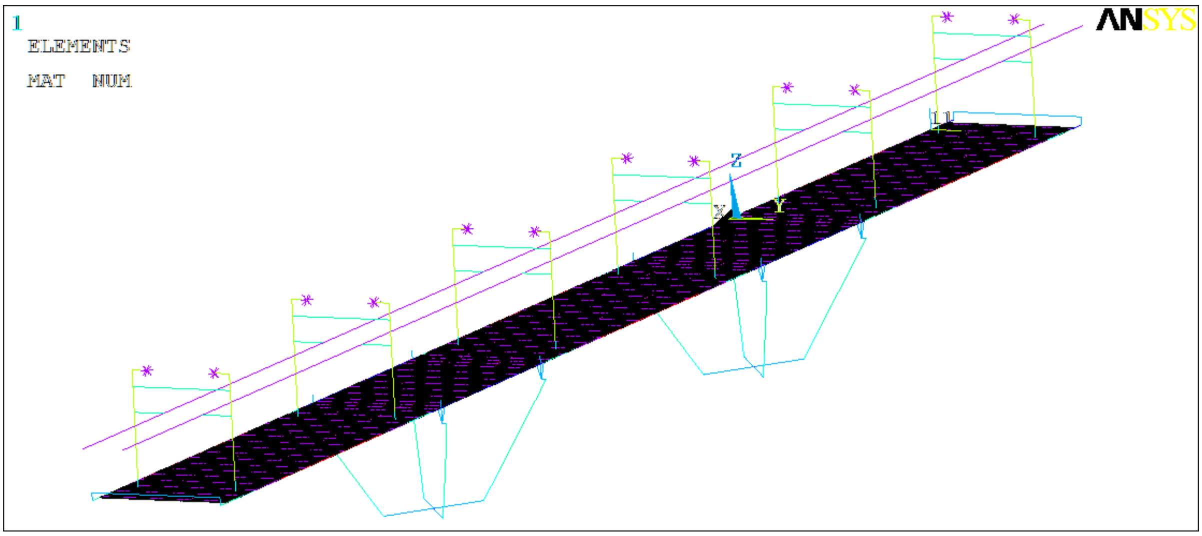

Figure 21: FE model of the Savoureuse bridge with crossbars on the catenary poles

The results for this FE model are given in Figure 22.

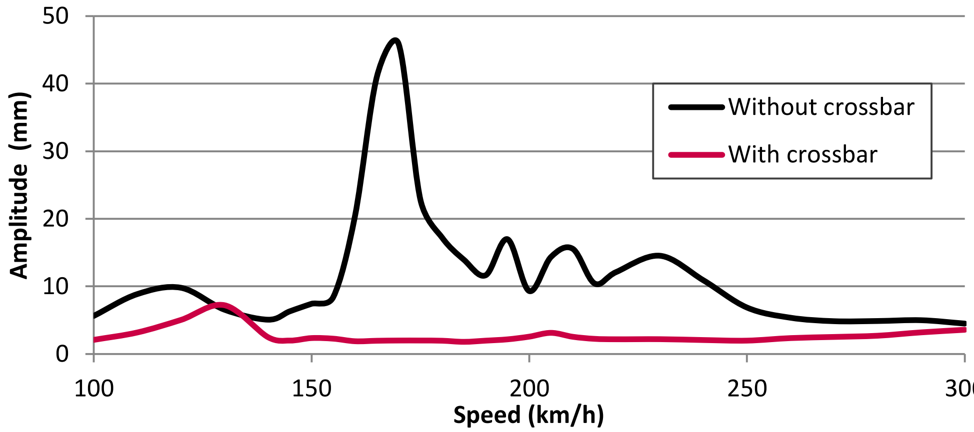

Figure 22: Comparison of the transversal displacement amplitude with and without crossbar

It is clear that the addition of the crossbar is very efficient. However, this solution presents the disadvantages of being:

- Complicated and therefore expensive to implement: the operation would require among others to remove the line feeder and the earth wires.
- Too rigid for maintenance: the position of the crossbar being constrained by the isolation distance it will not be possible to raise the contact wire if needed.
- Quite unsightly on a bridge designed by an architect.

4.3 Setting of Tuned Mass Dampers

Tuned Mass Dampers (TMD) presents interesting characteristics to improve the response of slender structure with low damping ratio (typically the case of catenary poles). They consist in adding a small mass to the structure with a certain stiffness and additional damping. The stiffness of the added system is adjusted to the eigenmode frequency of the main structure, so that the added mass resonates at the same excitation as the main structure. The additional damping dissipates quickly the energy of the resonance.

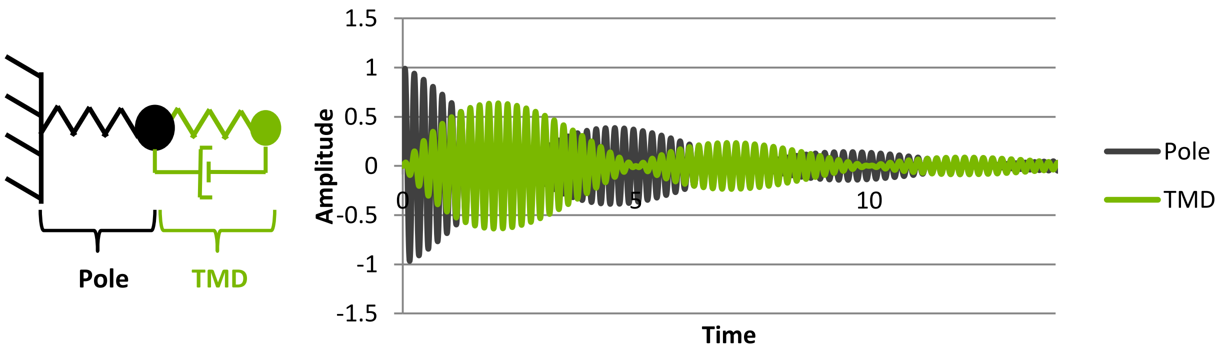

Figure 23: Functioning principle of Tuned Mass Dampers (TMD)

For the catenary poles of the Savoureuse viaduct, the TMD were imagined to fit in a box that could be fixed onto the poles. It was then calculated that the whole system could be located in a 1.2 x 0.18 x 0.18 m box. This box could therefore be fixed inside the flanges of the HEA240 girders for more discretion and aesthetics.

This TMD is composed of a mobile mass fixed on a stainless steel rod turning around a pin at the top of the box. The rod ends at the bottom with a piston able to dissipate the energy in a viscous fluid. The transversal movement of the catenary pole leads the mass to rotate around its axis as a pendulum. The frequency of the mass is adjusted with the height of the mass on the steel rod.

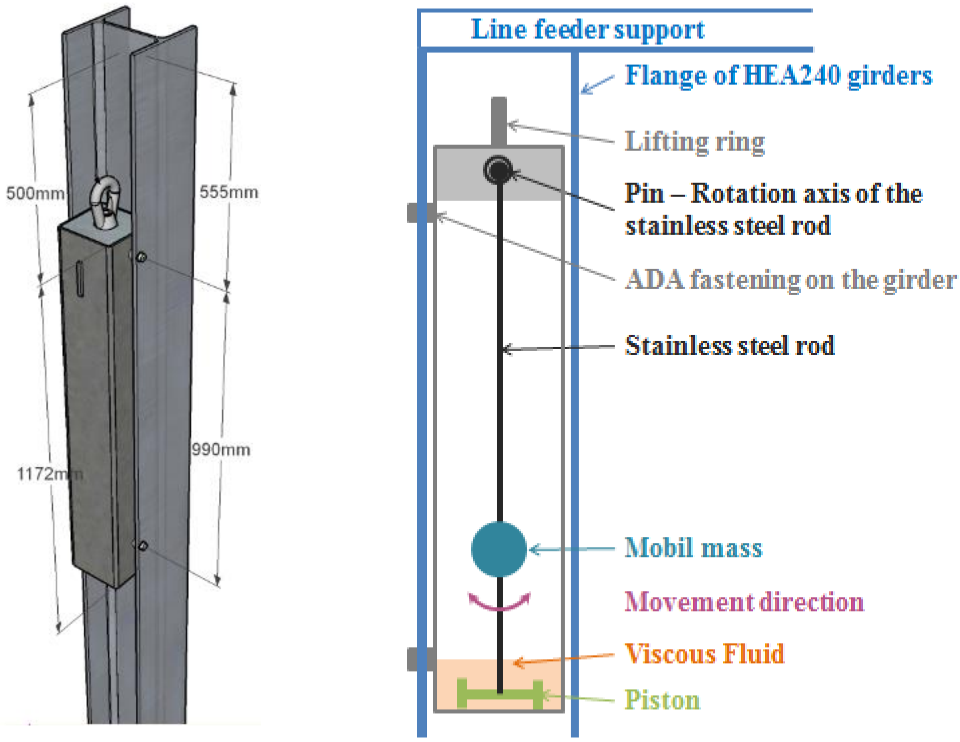

Figure 24: Diagram of TMD for the catenary poles

The effect of these TMD was calculated on the FE model of the bridge.

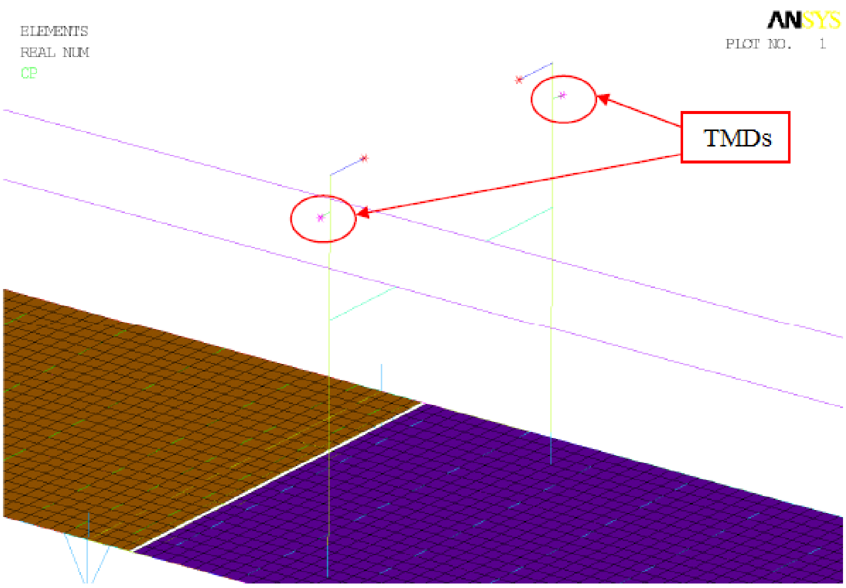

Figure 25: FE model of TMDs on the Savoureuse viaduct

The results of such calculations are shown in Figure 26 regarding the height of the TMD on the girder. It can be seen that when the TMD is placed relatively high on the girder, the system is very effective (displacement reduction around 80%).

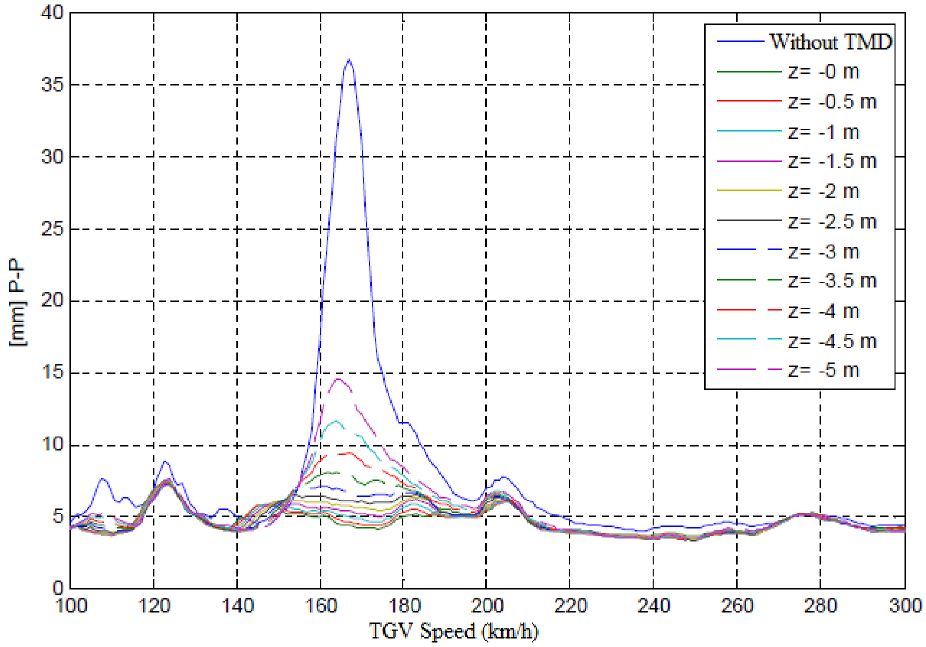

Figure 26: Comparison of the transversal displacement amplitude without and with TMD at different heights

This solution seems to be very efficient and presents different advantages:

- The TMD is easier to set than the crossbar, with a lower calculated implementation cost
- There is less impact on maintenance than the crossbar. The maintenance actions for TMD were identified in a document and adapted to the existing maintenance of the catenary poles.
- The solution is more aesthetic than the crossbar.

In consequence, it is the solution taken on by RFF.

5 IMPLEMENTING TUNED MASS DAMPERS

The TMD were set on the catenary poles of the viaduct and measurements were made before and after their implementation to verify their efficiency.

In a first step, two Φ14mm holes were drilled in the HEA 240 flange. To assure the exact positions of the holes, a drilling template was used.

Figure 27: Drilling in the girder flange

The TMD was then lifting by a crane and fixed with 2 M12 stainless steel bolts. A spacer was placed between the TMD and the girder flange in order to let the air circulating around the TMD.

At the moment of this article writing, only 6 TMD were implemented as a test phase. The equipment of the catenary poles with TMDs has proven to be very easy. The rest of the TMDs will be set in March 2015.

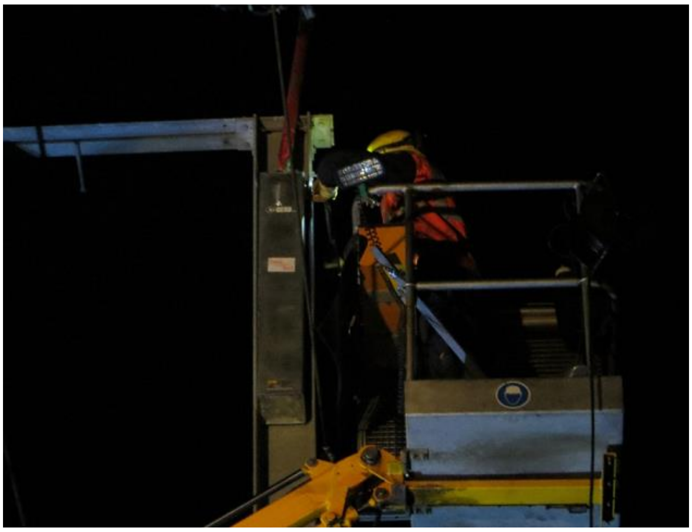

Figure 28: Lifting and fastening of the TMD

The signal measured on top of the pole after the implementation of TMDs was very different than the original signal (See Figure 29). It has to be noted on this figure that the scales of both curves (before and after) are different.

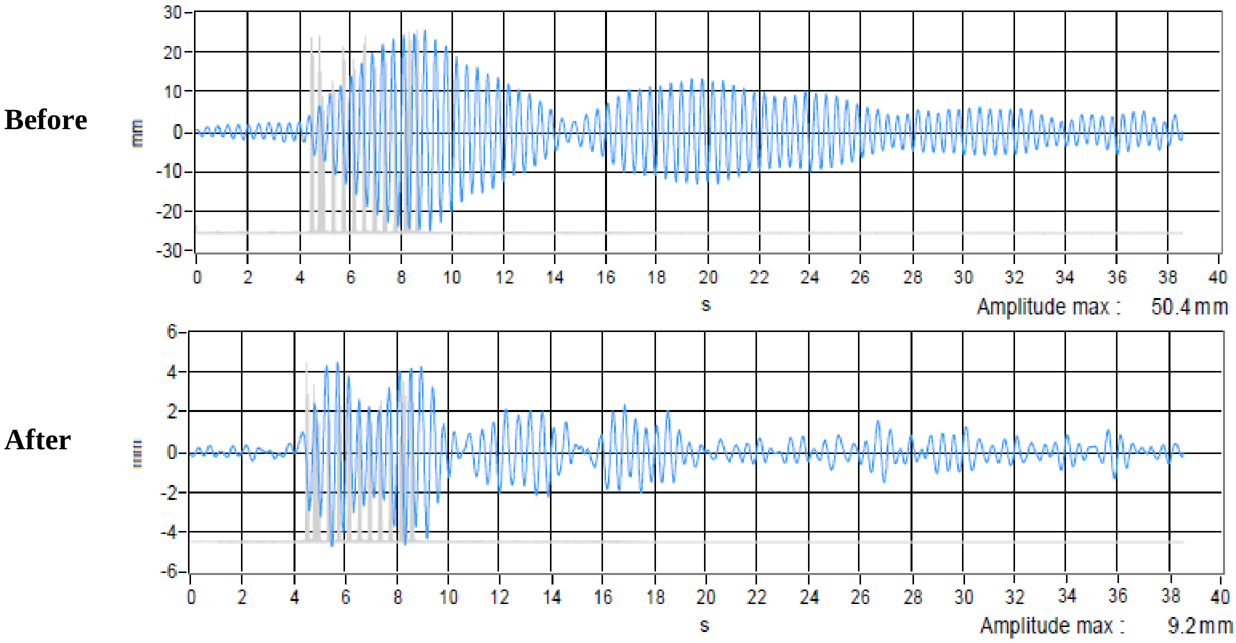

Figure 29: Comparison of the transversal displacement amplitude without and with TMD

It is clear according to this figure that the TMD is very efficient. The following figures show the maximum measured amplitude, the percentage of displacement reduction and the measured damping for the 6 catenary poles equipped with TMD. As it is a system composed of different coupled oscillator, it was not easy to determine the exact damping of the poles. This value was calculated by logarithmic decrement on 1.5 seconds after the train has left the bridge just before the beating phenomenon. This period is relatively short and sometimes the beating phenomenon starts earlier. The values given in Figure 32 should therefore be taken as average values.

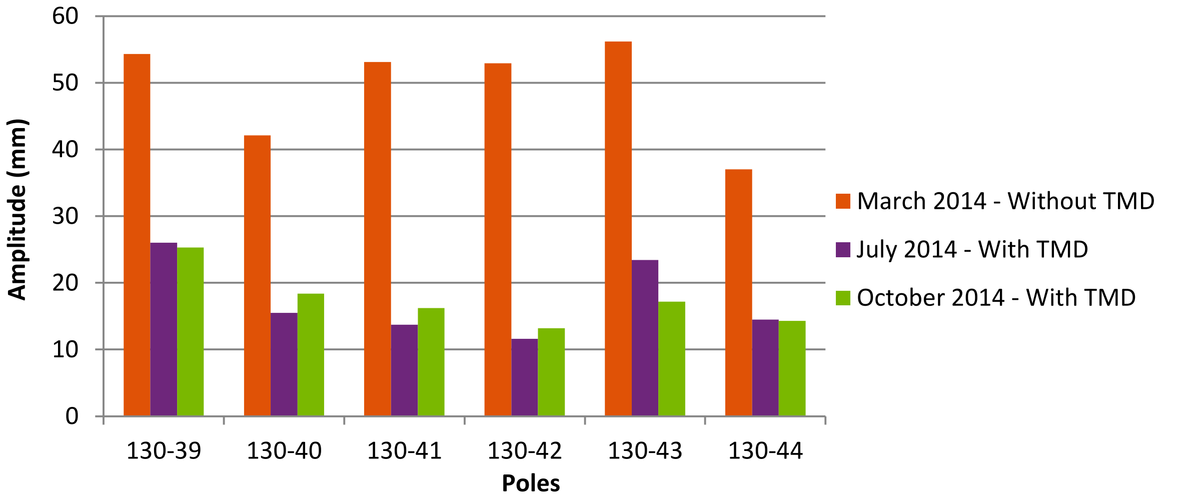

Figure 30: Comparison of the transversal displacement amplitude without and with TMD

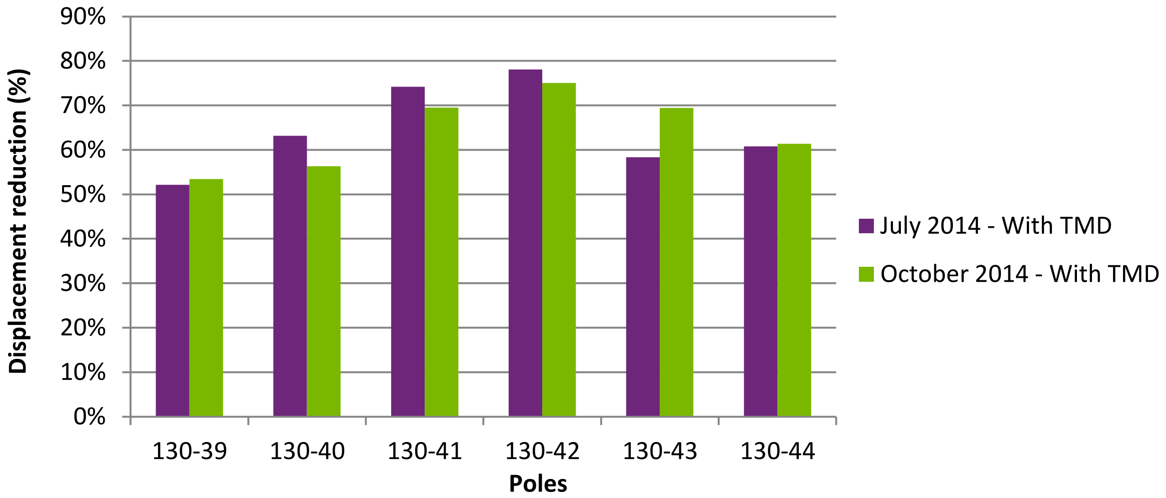

Figure 31: Reduction of the transversal displacements with TMD

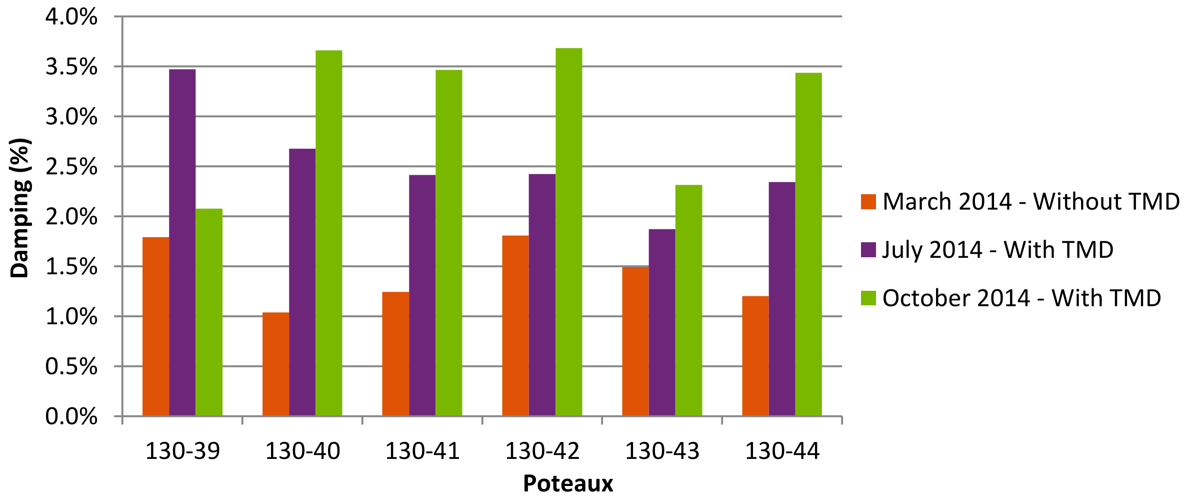

Figure 32: Comparison of the whole system damping without and with TMD

From the above figures, it can been seen that the displacement reduction obtained for catenary poles number 130-41 and 130-42 reaches 75% in average. This value is very close to the 80% obtained by the FE model. These 2 poles are surrounded by poles 130-39, 130-40, 130-43 and 130-44, themselves equipped with TMD. The efficiency of the TMD is then maximal on these 2 poles. For the 4 other poles, the displacement reduction is lower (around 55% in average). This can be explained by the fact that their neighbouring poles have not been equipped yet with TMD. These 4 poles are therefore still sensible to the vibration of these other non-equipped poles. It is expected that when all the poles will be equipped with TMD, the displacement reduction obtain for all the poles will turn around 80%.

For most of the poles, it can be noticed that the damping ratio has notably increased from 1.2% to 3% in average.

6 CONCLUSIONS

- This transversal vibrations phenomenon of catenary poles on a railway bridge was first observed in France in 2011 on the Savoureuse viaduct.
- It was shown in this study that the resonance the poles are subjected to is created by the transversal flexion of the bridge slab on which the poles are fastened.
- FE models and analytic calculations highlighted that the effect of the different wires of the catenary (messenger and contact wires especially) was very important on the global response. Therefore, they had to be taken into account to understand the phenomenon and to design an adapted solution.
- This phenomenon was never observed before because it is linked to a combination of parameters: bridge type (stiff lateral girders with a long transversal slab), train type and speed (TGVs at 170 km/h when stopping at a train station) and position of the poles at quarter span and on the slab close to the track where the rotation is maximal.
- The best solution found to reduce the poles resonance was to set Tuned Mass Dampers on top of the catenary poles.
- SNCF is now thinking about updating some of the rules for the design of catenary poles on railway bridges. Internal reference document will be modified to take this phenomenon into account.

REFERENCES

[1] P. Chapas, Alimentation en énergie des trains – Distribution de l’énergie électrique, Techniques de l’Ingénieur, Ref. 42576210, November 2012

[2] J. Schifter, The Effects of Bending Stiffness on the Dynamics of Catenary Cables, Master thesis, Massachusetts Institute of Technology, August 1996

[3] M. Del Pedro, P. Pahud, Mécanique vibratoire : systèmes discrets linéaires, Presses polytechniques et universitaires romandes, 2003, ISBN 2-88074-243-9

[4] B. Garnier, Isolation antivibratoire et antichoc – Solutions technologiques et industrielles, Techniques de l’Ingénieur, Ref 42424210, May 1994