VIBRATION OF LIGHTNING PROTECTION CABLES ON RION-ANTIRION BRIDGE

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Introduction

The Rion-Antirion bridge is a major cable stayed structure upon the golf of Corinth in Greece. On the 27th of January 2005, the bridge has been struck by lightning, leading to the failure of one stay cable. The improvements of the lightning protection system consisted, among other provisions, on the installation of stretch stainless steel ropes above the stay cables. These cables were not initially designed to avoid wind excitation and were prone to severe vibrations under usual weather conditions.

PRESENTATION

Lightning is a very common weather phenomenon and probability that a standing structure will be hit by a thunderbolt is not negligible. Large vertical cable structures are particularly prone to lightning impact because of their size, their height and metallic cables conductivity. On the 27th of January 2005, the Rion-Antirion Bridge, one of the longest multi-span cable stay bridges, has been impacted by a lightning strike which created a fire on one of the upper stay cables, leading finally to the collapse of this stay cable.
The best protection of large structures against lightning consists in conductive cable net surrounding the protected area, the aim of which is to offer a preferential way for electrostatic charges to translate from earth to clouds. This kind of Faraday cage is commonly used in rockets launch pad.
After a series of laboratory tests at full scale that clarified the reasons of the fire one of the strategies used for the enhancement of the lightning protection system for the Rion-Antirion Bridge consisted in installing stretch wires above the stay cables in order to intercept most of the lightning flashes [1].

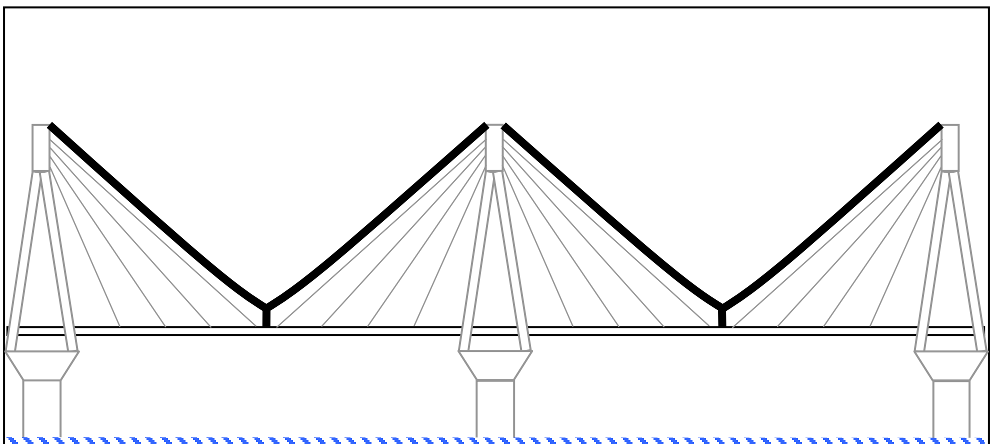


Figure 1 : principle of the stretch cables protecting Rion-Antirion bridge stays from lightning

Several reasons existed to justify separation of the lightning protection cables from the suspension stays, among which the will to keep the upper stay shape unchanged for aerodynamic purpose.
The choice of stainless steel ropes for the protection cable lead to an assembly of three ropes of common diameter in order to achieve the required conductivity and to create a redundancy in case of lightning damage of one of them. The three ropes were bound together with intermediate collars at specific interval locations..
After these three ropes cables were installed vibrations occurred, as reported by eye witnesses. A rapid analysis concluded at this time it might be vortex shedding excitation and the cable provider installed Stockbridge dampers in May 2006 and air flow spoilers, consisting in an helical strake of limited length running around the three ropes, in august 2006.
After 9 month observation by frequent close visual inspections it was concluded that:

- Stockbridge dampers were efficient in mitigating cables vibrations but they suffered fatigue and were removed in October 2007 before parts fall down on the road.
- Air flow spoilers didn't avoid cables vibrations and were accused to generate new torsion excitation.
- The lightning protection cables themselves were suffering fatigue and some broken wires were reported, where stress concentration occurred at some deviation collars.

At this stage a deeper investigation was decided before choosing another mitigation technique. Twelve channels of the bridge monitoring system, out of 372, were used to monitor three lightning protection cables with six 2D accelerometers in December 2007. Four months records of vibrations, wind speed and wind direction at a rate of 100 Hz were transmitted to CSTB for analysis.

FULL SCALE DATA ANALYSIS

Rion Antirion bridge in orientated 20° from a north-south line. The wind direction influences both the aerodynamics of the cables and the turbulence level of oncoming wind. Wind from north-east is less turbulent than from east direction for instance, due to steep hills surrounding.

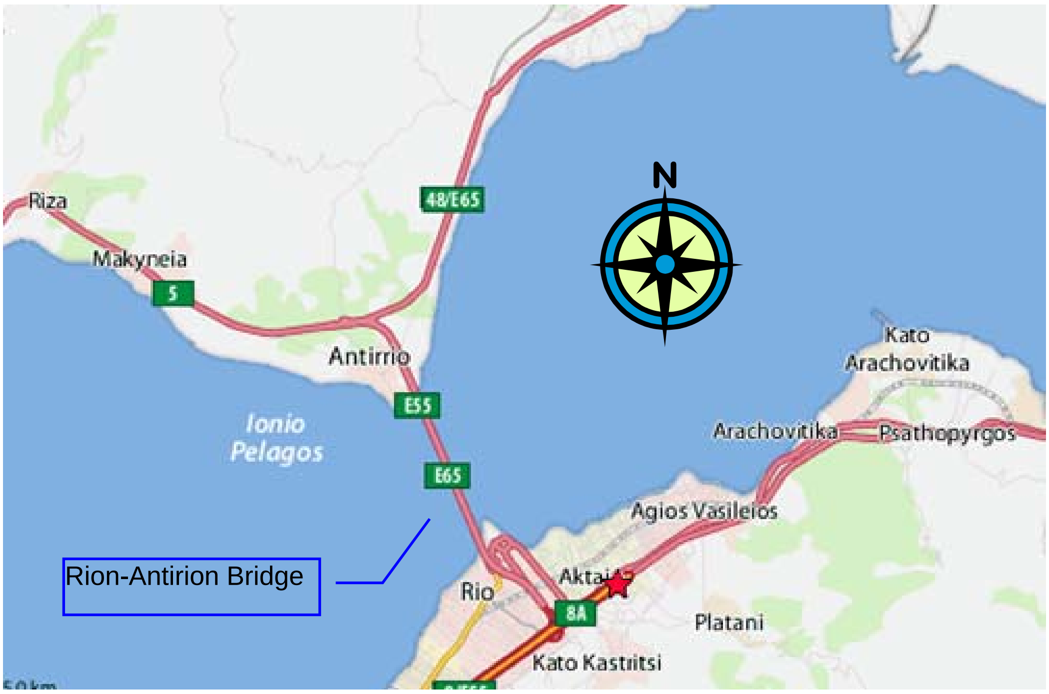


Figure 2 : bridge orientation compared to compass and hills surrounding

As usually observed in full scale measurement there are possibly many sources of cable vibration: vortex shedding, galloping, parametric excitation may be responsible for vibrations of the same cable at different times or locations. The first concern here was to look for a correlation between wind events and recorded large amplitudes of cables.

Looking at wind speed history compared to RMS value of accelerations it was obvious that wind speed modulus was not the only parameter governing cable excitation because many strong wind events did not correspond to large vibration amplitude and contrarily many large amplitude movement occurred with moderate wind speed.

A first ranking of data was realized as strong, moderate, light vibration or no vibration that was plotted against wind speed and direction. This showed a difference in the wind speed required to produce moderate or strong vibration with wind direction, especially for easterly wind. For westerly winds, coming from the open sea, there was no difference in amplitude whatever the wind direction. This first analysis confirmed that vibration was linked to oncoming wind turbulence intensity.

The wind speed threshold above which moderate or strong vibrations occurred was close to 6 m/s for westerly winds and wind directions surrounding 65°, but it was higher than 15 m/s for winds coming from directions close to 95°, after passing upon a mountainous area. This threshold was minimum for wind direction normal to bridge axis.

Comparison of vibration occurrences on the three monitored cables showed they didn't happen at the same time. Eye witnesses confirmed cables of the same length on the same pylon did not usually vibrate together.

The dynamic analysis of recorded data showed that large amplitude vibrations occurred mainly for 1.1Hz frequency and its harmonics for the 299m long cable referenced M4NE.

Cable ropes are made of austenitic stain less steel grade ASTM AISI 316, open spiral strands with 19 wires 3.18mm organized as 1+6+12. The whole rope diameter is 16mm, it weights1.24 kg/m with a nominal tension of 180 kN. The cable, composed of three ropes, 299m long, should have a first mode frequency of 0.37Hz. The third mode of the cable was this way mainly excited in this example. At the same time frequencies measured on the deck in the vertical direction were 0.255Hz and 0.412Hz, corresponding to the two first vertical modes of it and on the pylon 1.58 Hz.

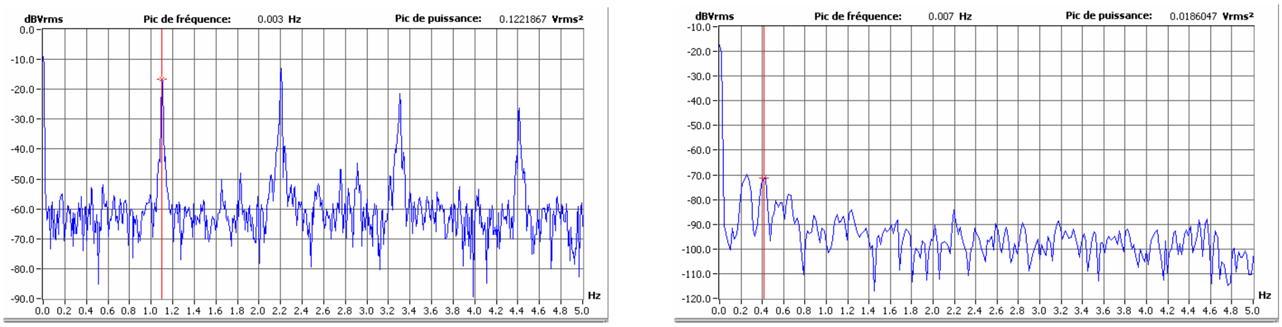


Figure 3 : PSD of cable M4NE (left) and bridge deck (right) vertical acceleration during a large amplitude event.

From these observations it was deduced the large amplitude vibration was not a parametric excitation kind, but its dependency to wind proved it could be a purely aerodynamic phenomenon. Therefore wind tunnel experiments were undertaken in order to verify these assessments and look for efficient countermeasures.

WIND TUNNEL STATIC TESTS

A piece of rope was provided in order to build a wind tunnel sectional model. Three ropes were first joined together in the shape of the actual cable referred as the "compact arrangement" (figure 4), this way the wind tunnel model was representing the whole shape and the strands. Sectional model was 1.5m long.

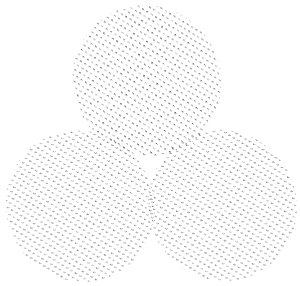
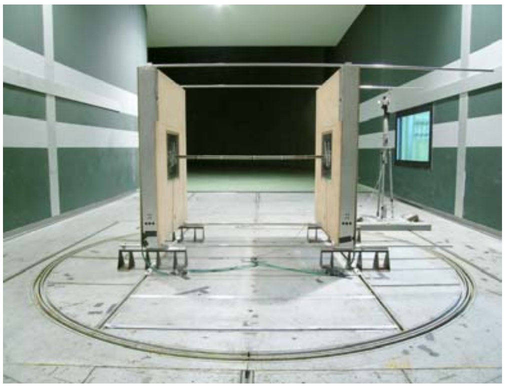


Figure 4 : shape of the actual cable referred as “compact arrangement”



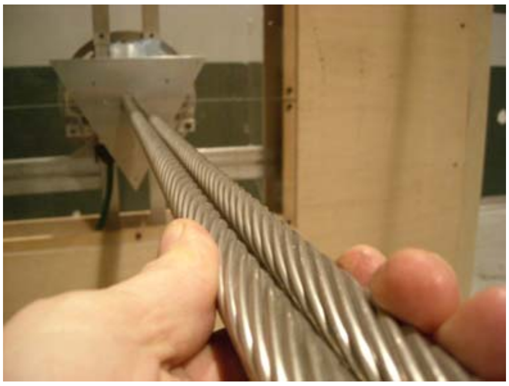


Figure 5 : model on supporting frame in wind tunnel

Model was build with high concern for its shape on a flat reference surface. The three ropes were glued together in order to provide stiffness and avoid twisting or bending deformation. Both ends were bound to two supporting three components balances hidden in a rigid frame situated in the middle of a 6m wide x 5m high wind tunnel. The rigid frame maintained 2 dimensional wind conditions without development of a boundary layer on edge panels.
The model was set horizontal. The force coordinates was chosen in order to exhibit symmetry, actual wind normal to bridge axis corresponding to -60° or +90° incidence. Drag and lift coefficients in the wind coordinates Cdrag and Clift were measured for wind speed 5, 10 and 15 m/s and incidence ranging from -90° to +90°. As shown Figure 7 they were not symmetrical on both sides of 0° incidence, what may be explained by stranding of wires.

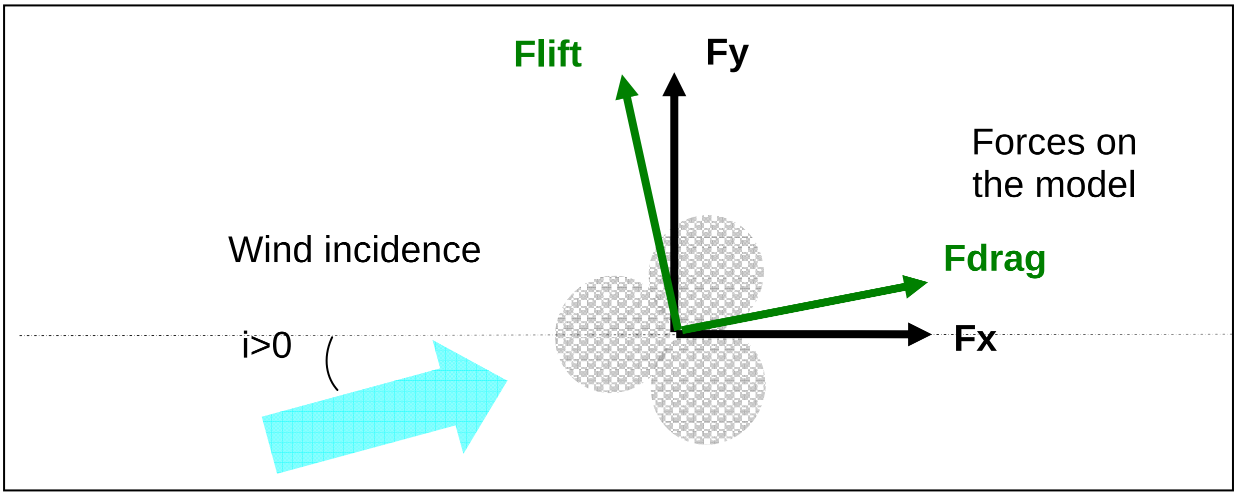


Figure 6 : force coefficients coordinates for compacted arrangement study

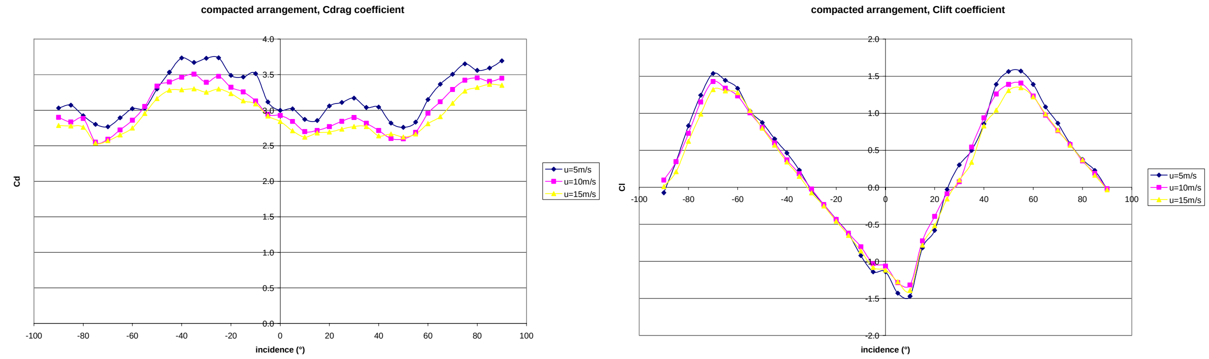


Figure 7 : Compacted arrangement, Cdrag coefficient (left) and Clift coefficient (right) for wind incidence varying from -90° to +90°

The slope of the lift coefficient in cable coordinates Cy (figure 8) reached twice a negative value of -1 in the wind incidence range, close to -60° and +90° that broadly corresponds on the actual bridge to wind perpendicular to bridge axis.

The Scruton number for this cable , $Sc = \dfrac{2 \times m \times d}{\rho \times D^2}$, calculated from damping decrement

d=0.001measured on site, cable mass m=1.24x3 kg/m, air density ρ=1.2 kg/m3 and cable apparent diameter D=0.016x2 m, reached the value of 6, indicating a real capability of galloping for this ropes arrangement.

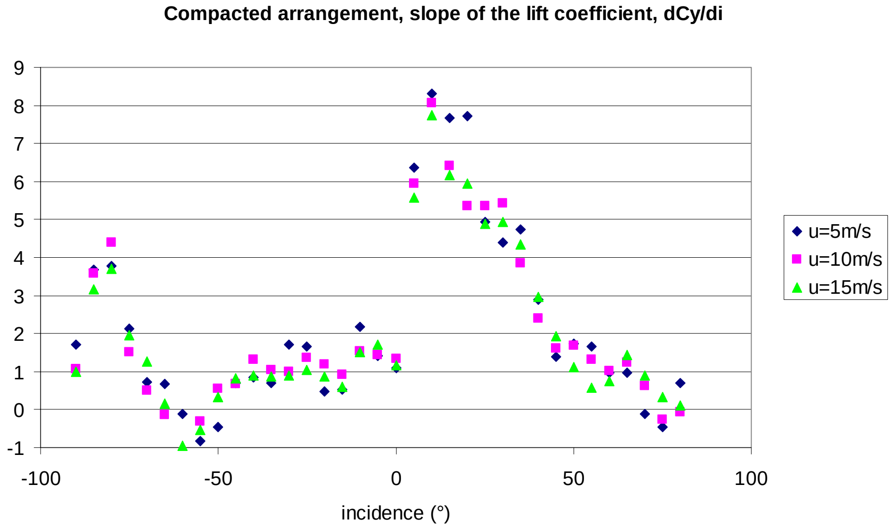


Figure 8 :Compacted arrangement, Cy coefficient slope variation with wind incidence

Another rope arrangement was suggested and its stability measured in wind tunnel.

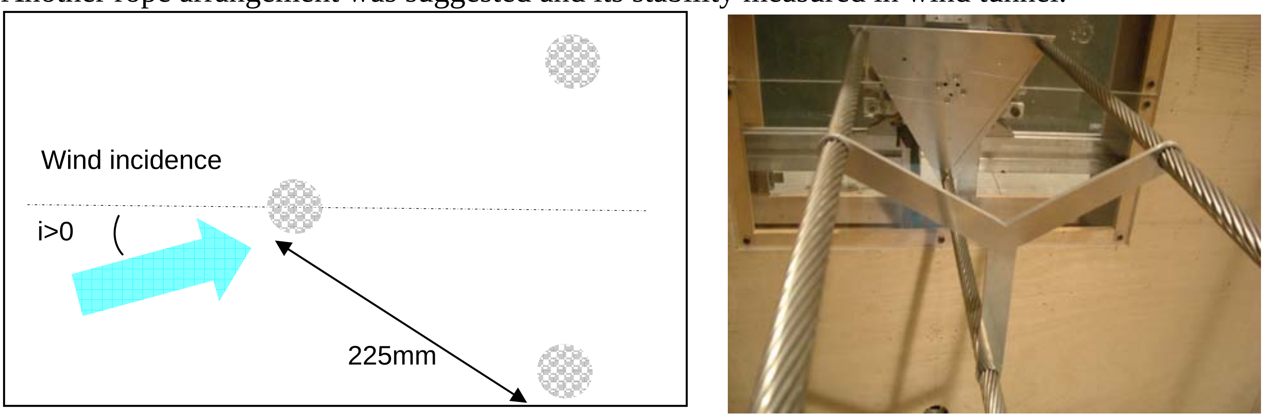


Figure 9 : force coordinates for spaced out arrangement of ropes proposed

This arrangement was called “spaced out” because the three ropes were maintained separated by 225mm by a thin metal spacer.
The same measurements as for the compact arrangement were realized in wind tunnel showing (figure 10) that force coefficients Cdrag and Clift were very uniform regarding wind incidence. With this arrangement Cy slope never became negative as shown figure 11. As a first conclusion, changing the arrangement of ropes could be an elegant solution avoiding lightning protection upper cable galloping. At the same time, cable supplier’s preferred solution was to install viscous dampers at the lower end of LPUC, what means no major work on the bridge, but aesthetically not the preferred solution by the owner. Dynamic modeling in wind tunnel was achieved in order to evaluate this dissipative solution.

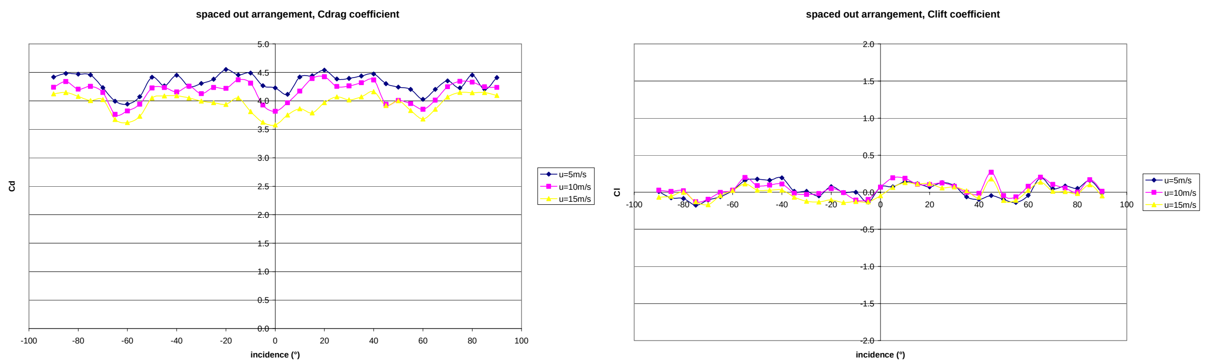


Figure 10 : Spaced out arrangement, Cdrag coefficient (left) and Clift coefficient (right) for wind incidence varying from -90° to +90°

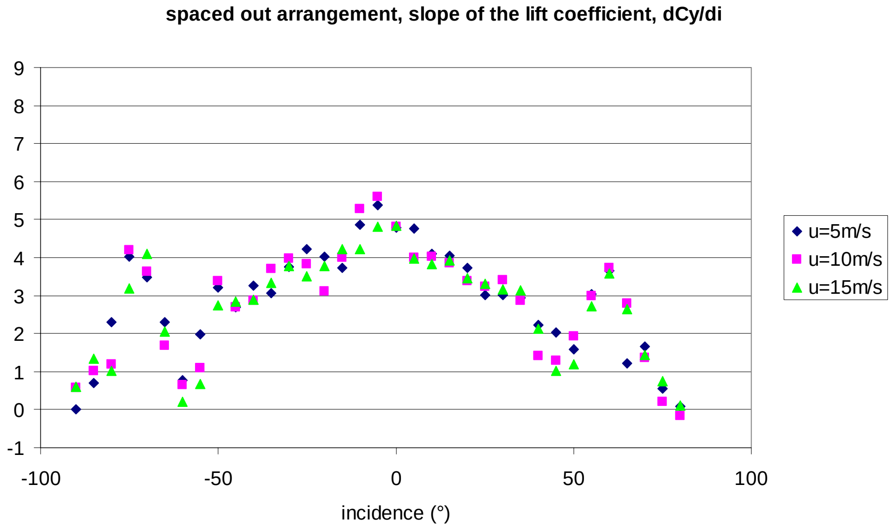


Figure 11 :Spaced out arrangement, Cy coefficient slope variation with wind incidence

WIND TUNNEL DYNAMIC TESTING

Both sectional models designed for force measurement were used for dynamic testing. Because models had been realized with actual pieces of ropes and included end plates and supporting devices, final model mass was 50% higher than actual cable.
It was suspended horizontally to springs arranged in a way vertical oscillation only can occurred at frequency 1.1Hz with a damping decrement d=0.004. Model and supporting rig were installed inside the 4m x 2m section of a low turbulence wind tunnel.
This time models were oriented in a way 0° wind incidence in wind tunnel corresponds to wind normal to bridge axis on site.
For the compact arrangement cable strong vibrations were observed at incidence 0° and 1° and at 54° to 56° for wind speed as low as 4m/s.

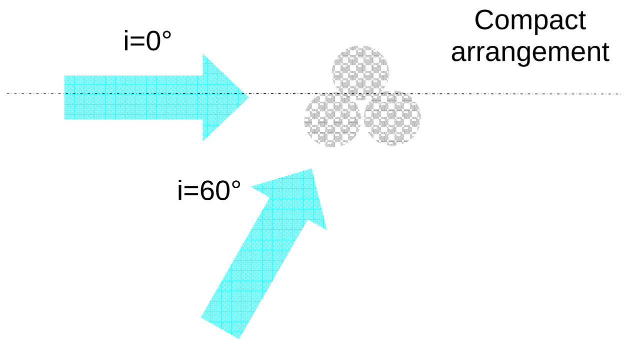


Figure 12 : Coordinates for dynamic testing of compact arrangement of ropes

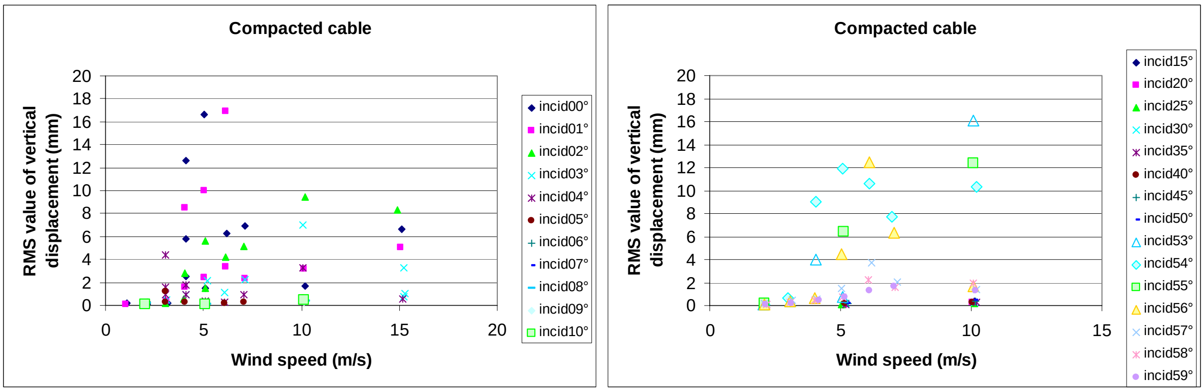


Figure 13 : Aeroelastic response of compact arrangement cable with wind speed, amplitude in mm.

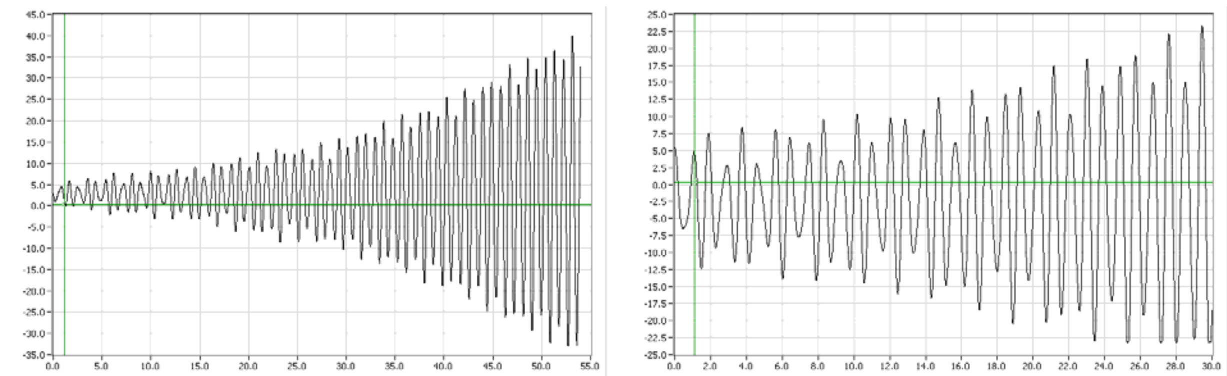


Figure 14 : increasing amplitude of compact arrangement cable for wind speed 5m/s at incidence 54° (left) and 1°(right).

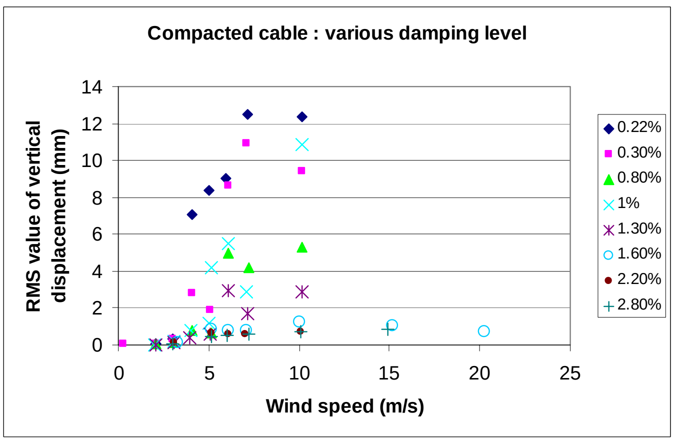


Figure 15 : Effect of increasing structural damping on galloping amplitude of compact arrangement cable.

For the incidence considered worse, 54°, mechanical damping was increased step by step in order to look for the minimum damping able to mitigate galloping. Fig15 shows galloping was not suppressed with damping level less than 1.3% of critical, that is decrement d=0.08.

Same kinds of tests were conducted for the spaced out arrangement cable without any vibration observed, whatever the wind speed and incidence. This gave another argument to guarantee this rope arrangement will suppress galloping excitation.

Various models of spacers had been suggested, some of them including a damping effect. For one model, consisting in a short PU cylinder, wind tunnel tests were realized in order to check the stability of the spaced out arrangement modified by this damper. No instability was observed in a wide range of wind speed up to 26m/s, for wind perpendicular to cable axis.

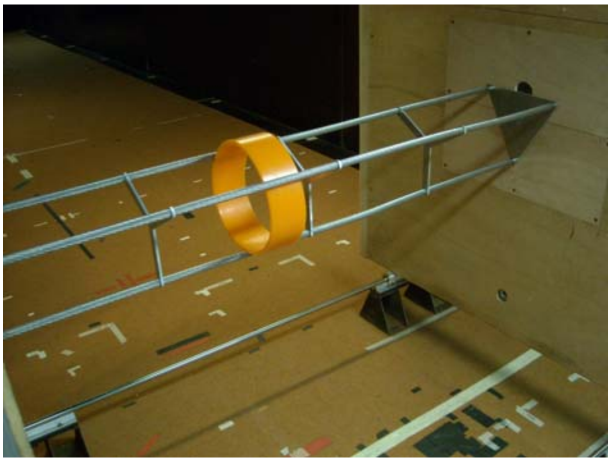


Figure 16 : Wind tunnel test of spaced out cable stability when equipped with a PU ring acting as a damping spacer.

CONCLUSION

Vibration phenomenon of Lightning Protection Upper Cables on the Rion-Antirion bridge was identified as galloping, due to the arrangement of the three constitutive ropes.
Another arrangement of ropes was proposed and wind tunnel studies showed its efficiency in suppressing the galloping phenomenon..
An alternative mitigation solution was damping increase by mean of viscous dampers. Wind tunnel tests showed this solution would be efficient only if a high level of damping could be provided.
Finally it was decided to change ropes arrangement with spacers providing additional damping.

REFERENCE

[1] A. Rousseau, L. Boutillon, A. Huynh, 2006, "Lightning protection of a cable-stayed bridge", *28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 september 2006*.