Conditions for occurrence of vortex shedding on a large cable stayed bridge. Full scale data from monitoring system

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Abstract

Monitoring systems are nowadays usually provided on large bridges, decision being taken as early as in the design process. After completion they are very valuable for providing data about the actual behaviour of the structure facing real wind that can usefully be compared to design models. The Charilaos Trikoupis bridge between Rion and Antirion, in Greece, was equipped with a very complete monitoring system including accelerometers on the deck, pylons and cables along the four spans and anemometers. This system is perfectly maintained by permanent staff from Gefyra company, the bridge's owner, and gives information about bridge's structural health that are regularly used for maintenance. This smart system records continuously only sparse data, complete dynamic check being achieved every two hours. This monitoring system was also designed for recording on trigger for special events. From recorded data, vibrations of cables have been observed after bridge completion and the bridge owner suppressed them within some months by installing dampers between deck and cables. Vertical vibration of the deck on the third mode was also observed at some occasions from records of the monitoring system, with limited amplitude. Gefyra asked CSTB for processing two years of monitoring data in order to fully understand the origin of this vibration and evaluate if applying a treatment would be necessary.

1 Introduction

Civil engineering structures like slender bridges are prone, in many occasions, to deformation under service loads. When such a deformation is repeated along time and corresponds to an oscillation around a mean state, we can speak about vibration. Traffic, temperature, earth movement and wind apply loads on such a bridge, the structure of which comes back to its stable state after the load ceased, with various typical times, i.e. various frequencies. For this reason vibrations are not exceptional on a bridge, they are just part of its casual behaviour, they only need being observed and analysed as checking they don't go over security thresholds. Vibrations induced by wind draw special attention because their origin could be considered negligible when their consequences can be much visible.

Vortex shedding is one of these phenomena that produce anxiety mainly because it gives way to detectable amplitude movements of the structure when the origin, a moderate wind, does not appear basically as yielding risks. This is particularly true on large bridges because numerous users give numerous testimonies when the deck is prone to an easy to see vertical displacement. This movement usually corresponds to small amplitude of deformation but on such a long line like structure this gives way to large amplitude of displacement at low frequency, what can be observed by anyone.

Both issues of vortex shedding excitation on a bridge deck are users' comfort till the acceleration will become noticeable to them and the risk of fatigue on the most exposed structural elements by repeated solicitation.

2 Monitoring system and data mining

The monitoring system of the Charilaos Trikoupis bridge was designed as convenient to follow up vibration of the deck in flexural bending and torsion as well as vibrations of stays, including measurement of wind speed on top of pylons. Therefore the monitoring system was perfectly maintained after the bridge was opened to traffic ; sensors were changed very fast if they went out of service, giving way to a monthly serviceability rate most of time equal to 100% and never lesser than 90% over all the period of study.

The monitoring strategy combines an alert mode, with high frequency record of all sensors signals when thresholds are exceeded and steady rate records for checking system good working order. This is this second part of the recorded data that was mined in order to extract the vortex shedding occurrences which usually lead to vibration level much lesser than thresholds for alert.

These steady rate records are of two kinds: every 2 hours a high frequency record of all sensors for 60 seconds duration is done and any 30 seconds the instant value of all sensors is also recorded in a separate file. Processing the every two hours records, hereafter named "Dynamic files" gives a number of vortex shedding occurrences corresponding to excitation of the third flexural bending mode, but not all of them because some occurrences of the phenomenon can last less than 2 hours.

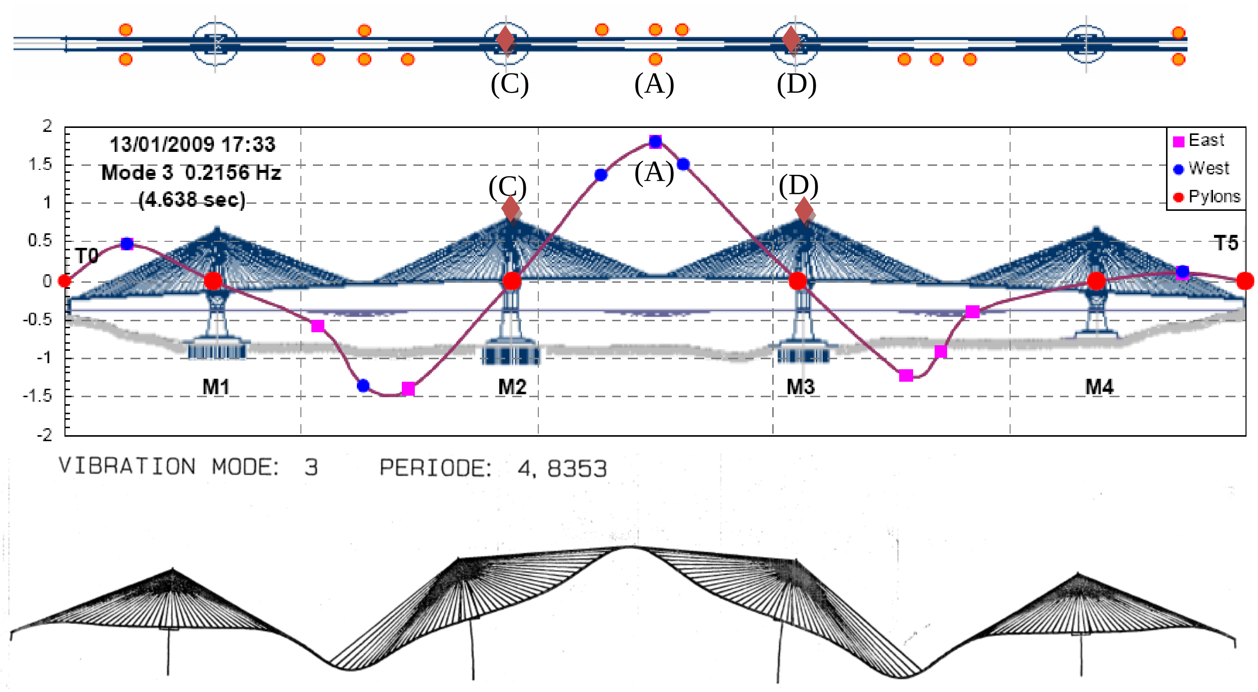

Figure 1 : Sensors locations and 3rd vertical mode shape of the RION ANTIRION Bridge.

In excess of the analysis of Dynamic files, the peculiar work described in this paper concerns a method used for processing the non continuous data taken every 30 seconds, corresponding only to the instant value given by sensors, as sentries of vortex shedding event. This work proves it is possible to count the vibration events over a long period using a reduced set of recorded sensors values.

3 Relationship between wind characteristics and the occurrence of vortex shedding

As wind data were available as well as some of the vortex shedding events captured by the every 2 hours regular records over a two years period including 2009 and 2010, it was experienced whether the wind force, direction and turbulence were main parameters of alternate eddies excitation or not.

Wind was most of the time normal to bridge axis and stronger from East than from West (Fig 2 and 3)

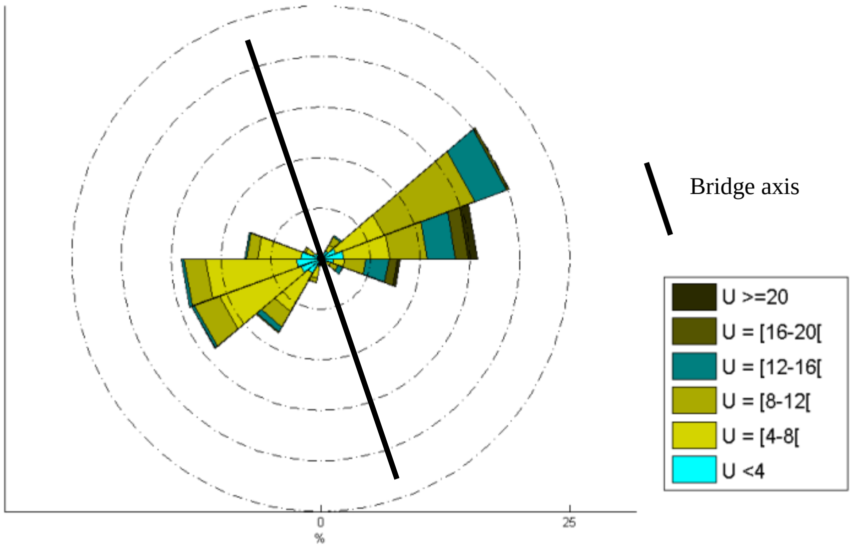

Figure 2 : Rose of wind mean speed, M1M2 anemometer, year 2009

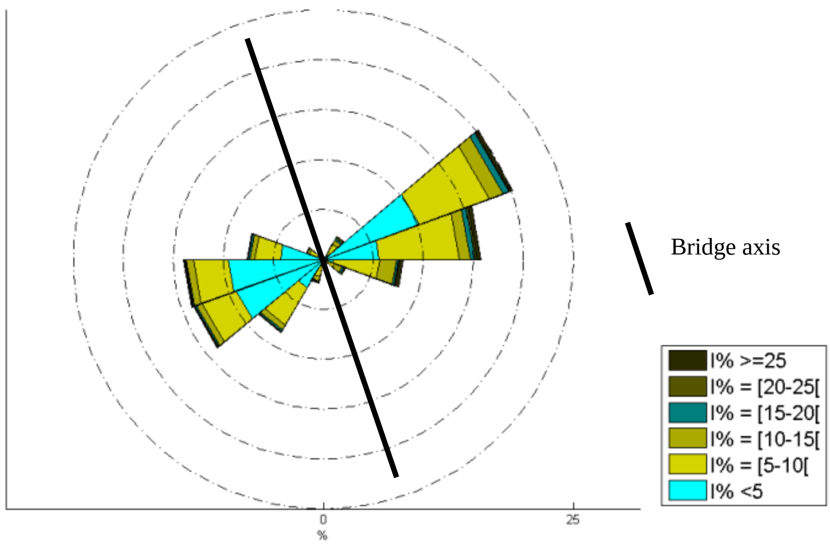

Figure 3: Rose of wind mean speed, M1M2 anemometer, year 2010.

It was first observed that the west wind turbulence was lower than the east wind turbulence for 2009 and 2010. The wind appears very smooth compared to usual Eurocode specifications. The Eurocode turbulence intensity for sea wind at 57m above the sea, the height of bridge deck, is over 10%. This reference was used for the design process, yielding to consider Iu=12% for the design wind speed. Full scale data show a turbulence level of 5% or less happening more than 50% of the time for western winds.

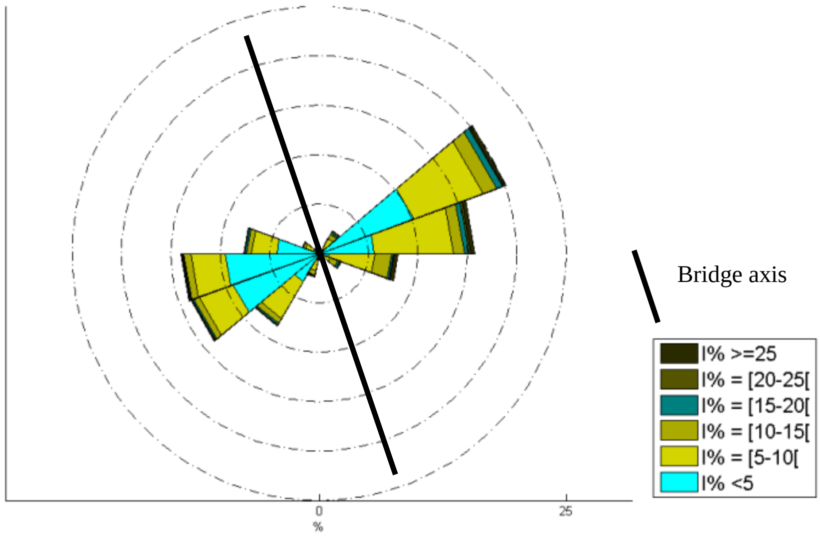

Figure 4 : Rose of wind turbulence intensity, M1M2 anemometer, year 2009

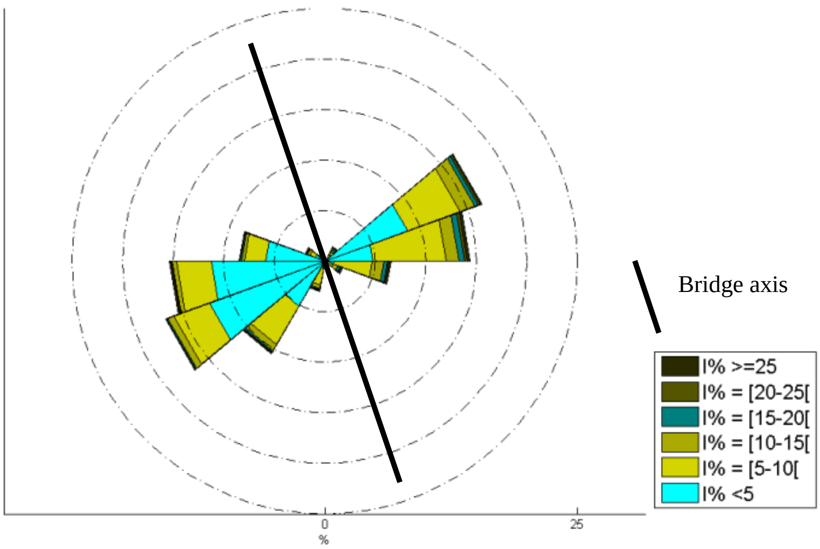

Figure 5 : Rose of wind turbulence intensity, M1M2 anemometer, year 2010

Figures 6 and 7 graphs present respectively the standard deviation (STD) of the acceleration of the deck in the vertical direction, measured at mid span, calculated from Deckaccelerometer 17E M2M3E E17E-Z (A) records versus mean wind speed and versus wind direction (sensor E) for all 2009 monitoring records. Red points on the drawing were identified as 2009 vortex shedding events, because their amplitude is much larger than usual, the vibration continuous and perfectly sinusoidal.

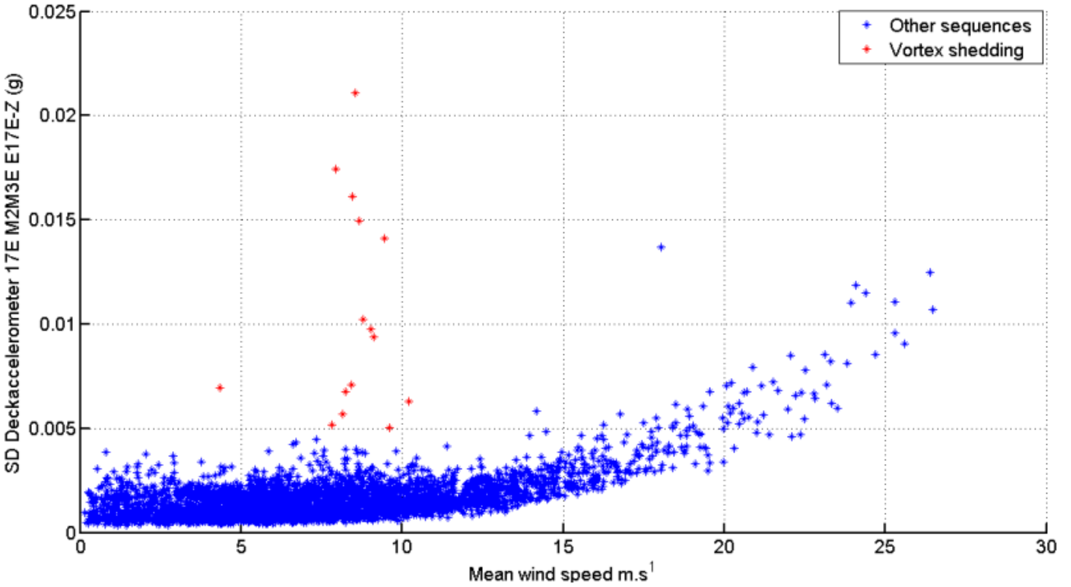

Figure 6 : STD Deckaccelerometer 17E M2M3E E17E-Z vs mean wind speed (2009, M2 PXI)

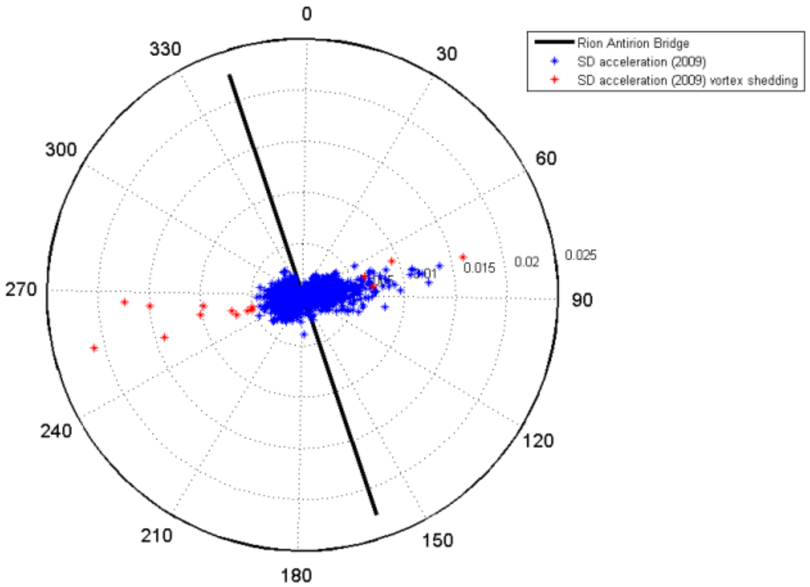

Figure 7 : STD Deckaccelerometer 17E M2M3E E17E-Z vs wind direction (2009, M2 PXI)

These 15 vortex shedding events, denoted by large acceleration amplitude at moderate wind speed, occurred mainly on west wind direction (~255°) as shown on figure 7. The average mean wind speed was 8.4 m/s. The average turbulence level was 2% (0.1-1 Hz bandwidth). This turbulence level is surprisingly low.

Figures 8 and 9 graphs present respectively the standard deviation of Deckaccelerometer 17E M2M3E E17E-Z (A) versus mean wind speed and versus wind direction (sensor E) for the 2010 monitoring. Red points correspond, the same way, to vortex shedding events.

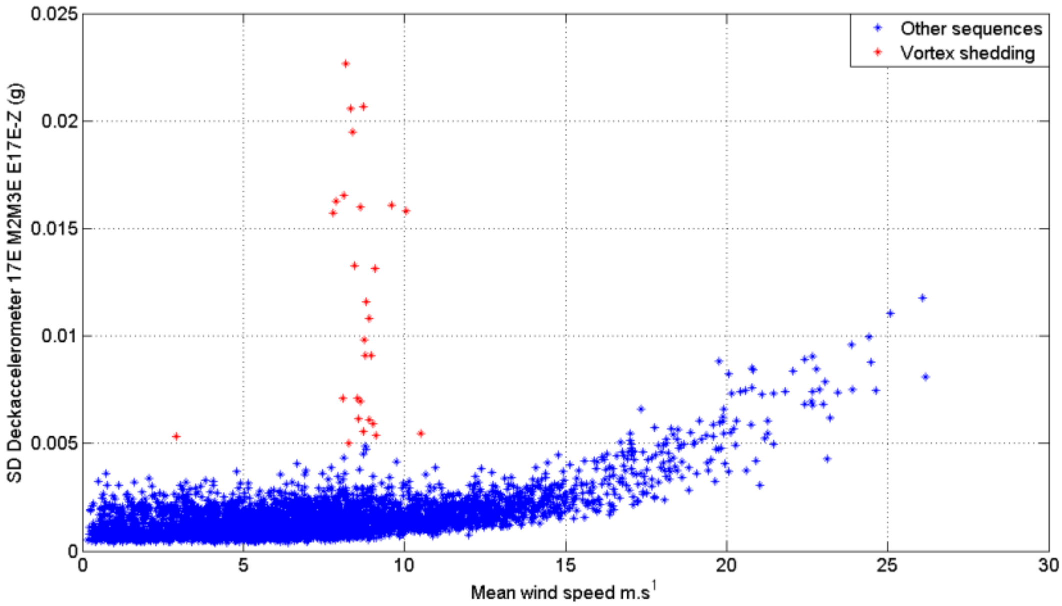

Figure 8 : STD Deckaccelerometer 17E M2M3E E17E-Z vs mean wind speed (2010, M2 PXI)

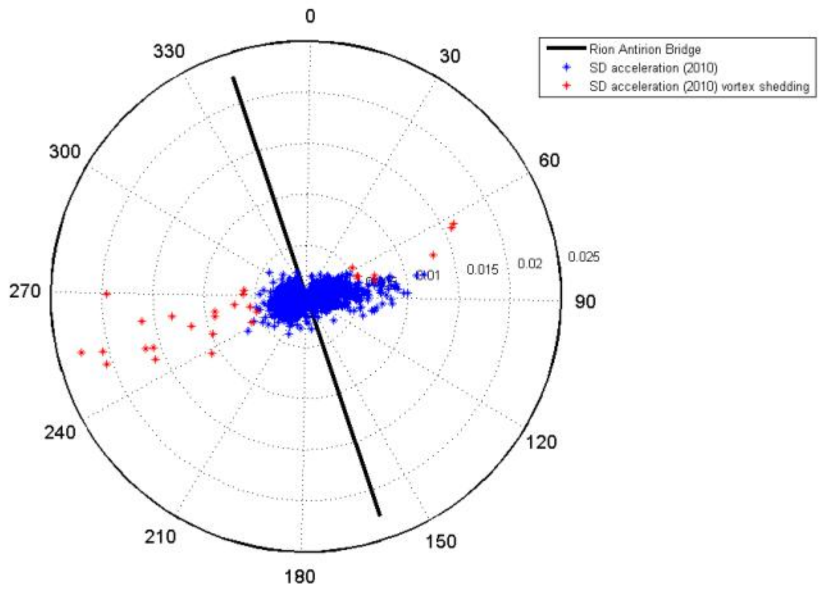

Figure 9 : STD Deckaccelerometer 17E M2M3E E17E-Z vs wind direction
(2010, M2 PXI)

The vortex shedding events occurred mainly on west wind direction (~255°). The number of event is 28. The average mean wind speed was 8.5 m/s. The average turbulence level was 2.5 % (0.1-1 Hz bandwidth).

It must be underlined that this limited value of turbulence intensity was calculated from short records (60s) that could not express the low frequency wind fluctuations giving way to turbulence. For this reason turbulence intensity calculated from Dynamic file records underestimates the actual variability of wind speed by comparison with turbulence issued from standard 10 minutes records.

The number of vortex shedding events in 2010, characterized by large amplitude at reduced wind speed and a quasi sinusoidal movement, was twice the one of 2009. Figure 10 illustrates a typical example of record of vortex shedding event. Third vertical bending mode only was mainly excited.

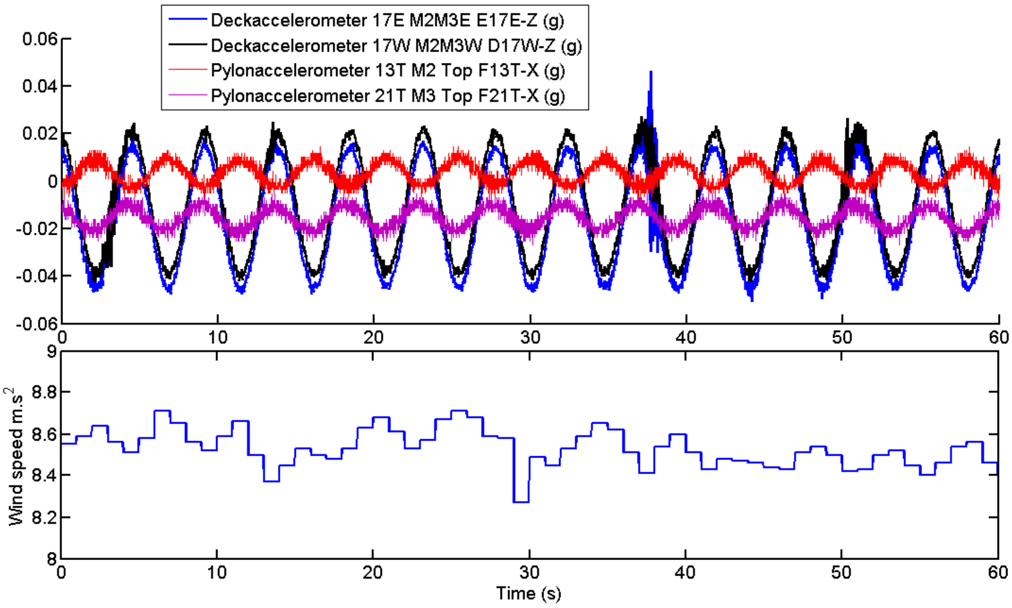

Figure 10 : Typical vortex shedding record (m2Dynamic record - 070609 22h00m.txt)

4 Reconstruction of vortex shedding events from instant records

As explained previously, processing the Dynamic files (60 seconds duration sampled every 2 hours) could not reveal every vortex shedding events, only 15 events in 2009 and 28 events in 2010 have been evidenced by this mean. However, these few events can serve as reference for a signal processing analysis to be carried out on the "Day history" files (one instant value every 30 sec) with the aim to detect and characterize every vortex shedding events (number, duration, maximum displacement). Day history files consist in averaged acceleration over 0.5 sec and a value recorded every 30 sec (sampling frequency 0.0333 Hz) for all sensors.

This signal processing consists first in the definition of the aliasing frequency of the 3rd vertical mode, fa = 0.015 Hz, what yields the useful spectral bandwidth of the "Day history" files = 0-0.0167 Hz, then apply a high pass filter (Butterworth) with the cut off frequency fc = 0.01 Hz (contains fa bandwidth) to the files and finally reckon standard deviation over a moving window of optimized size. As time signal for vortex shedding events proved to be rather sinusoidal, it was assumed the maximum amplitude could be deduced from the RMS value issued from this processing.

Each subsample is defined by:

N : Number of sample of continuous time series of data (i.e. size of the window),

Facq : acquisition frequency ;

The standard deviation of a subsample is defined by :

$$\mathrm{STDssamp}(t) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(xi - \overline{x_N})^2}$$

For a subsample x_N the calculation window could be centered of shifted backward :

$$x_N = \begin{cases} x\left(t - \frac{N}{2 \times Facq}\right), \ldots, x\left(t + \frac{N}{2 \times Facq}\right) \text{ (centered)} \\ \text{or} \\ x(t), \ldots, x\left(t + \frac{N}{Facq}\right) \text{ (backward)} \end{cases}$$

Both methods were compared for occurrences when Dynamic files have been recorded and can serve as "reference". Figure 11 shows that the centered method did not give the same time shift in the time localization of the maximum of amplitude, as the backward method induced. Therefore the centered method was preferred even if the determination of amplitude was no so accurate. The size of the calculation window was optimized too and a 5 minutes window was found best fitting the results from Dynamic files. This optimization is a balance between a reduced number of data (5 minutes window means STD is calculated only upon 11 values) and the duration of the phenomenon lying on natural wind steady state (less constant over a 10 minutes period than over a 5 minutes one).

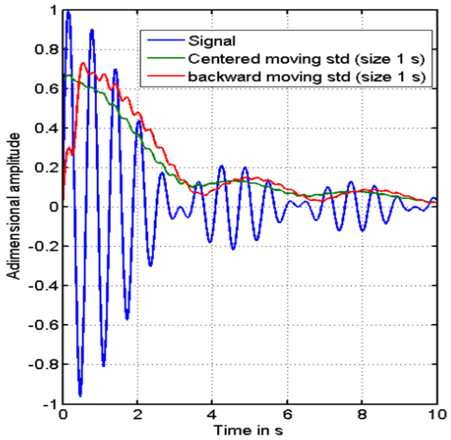

Figure 11 : Comparison of two methods for calculating the STD on Dynamic file

Finally occurrences of vortex shedding events were reconstructed over years 2009 and 2010 and showed that many short duration events haven't been detected by the traditional monitoring process.

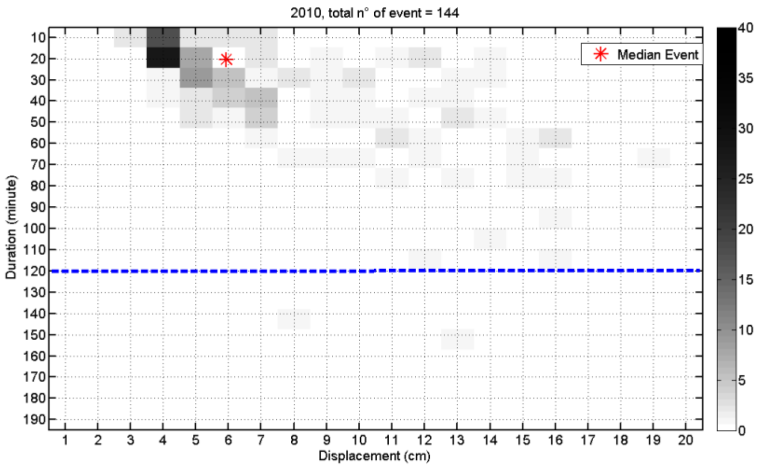

Figure 12 : Table of reconstructed vortex shedding events for the year 2010

References : O'CONNOR C. and SHAW P.A., "Bridge Loads", SPON PRESS, 2002.