Using Non Continuous Records from Full Scale Monitoring System for Fatigue Assessment

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USING NON CONTINUOUS RECORDS FROM FULL SCALE MONITORING SYSTEM FOR FATIGUE ASSESSMENT

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ABSTRACT

Monitoring systems are prone to record huge amount of data, only a minor part of which could be of interest. Maintaining a giant data base from the monitoring system of a large structure equipped with dozens of sensors is a costly challenge.

One way for solving this question lies in discarding everything that does not enter in the scope of what was considered as "interesting event" at the design stage, with a big risk of missing an unattended but essential event.

Another way could be to store less data, making a kind of "survey" instead of recording continuously, with a possibility to rebuild events from the discontinuous records. This way of doing is suitable in the case of minutes lasting phenomena only, it is clear that a sudden and brief phenomenon could be missed in such a configuration. This method was used in the case of vortex shedding excitation of the deck of a large cable stayed bridge, in order to rebuild the history of passed excitations and evaluate the risk of fatigue on some structural parts.

KEYWORDS : *monitoring, bridge, vortex-shedding, fatigue, sparse data.*

INTRODUCTION

The The Rion-Antirion Bridge, in Greece, was equipped with a very complete monitoring system including accelerometers on the deck, piers and pylons and cables along the five spans as well as anemometers. This system records continuously mainly sparse data. One single value, 0.5 sec average, of each sensor is recorded every 30 seconds, real dynamic data are recorded only every two hours with one continuous record of at least 60 seconds or during threshold overpassing.

During operation period, the bridge exhibited occasionally limited amplitude vibration of deck due to vortex shedding excitation. CSTB was asked to extend and improve the processing of five years monitoring data in order to assist the designer on estimating fatigue risk for crucial structural elements and to propose mitigation measures if required.

1 CHARACTERISTICS OF THE VORTEX SHEDDING PHENOMENON ON LARGE BRIDGES

Civil engineering structures like slender bridges are prone, in many occasions, to deformation under service loads. 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 to be observed and analysed to check that 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 risk. 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, observable by a user.

Vortex shedding, also known as Karman vortex excitation, is a moderate energy instability occurring when the frequency at which vortices are formed in the wake of a bluff body, like a bridge deck, corresponds to a modal frequency of vertical vibration of this deck. The shedding frequency depends on the wind speed. When the wind speed increases, the shedding frequency increases at the same rate. The so called Strouhal number St, introduced by Vincent Strouhal a Czech physician of the 19th century, gives the basic relation between frequency of shedding, f, wind speed U and the lateral to wind dimension of the body, B.

$$f = St \cdot \frac{U}{B}$$

Because natural wind varies in time and in space, the shedding frequency is not maintained for a long time in usual meteorological conditions, which is the reason why bridges are not prone to everyday excitation. But for unusually stable and long lasting wind conditions, vortex shedding can lead to an excitation of bridge deck in vertical direction, the duration of which ranges between some minutes and some hours with amplitude up to decimetres.

Vortex shedding excitation on a bridge deck concern users' comfort till the acceleration becomes noticeable to them and the risk of fatigue on the most critical structural elements.

2 VORTEX SHEDDING EVENTS ON THE RION-ANTIRION BRIDGE

2.1 Monitoring system

One of design considerations of the monitoring system of the Rion-Antirion Bridge was the follow up of the deck vibration in flexural bending and torsion as well as vibrations of stays, including measurement of wind speed on deck level. Due to proper follow up and maintenance of the monitoring system, the monthly serviceability rate equals to 100% most of time and never less than 90% during the period of current study.

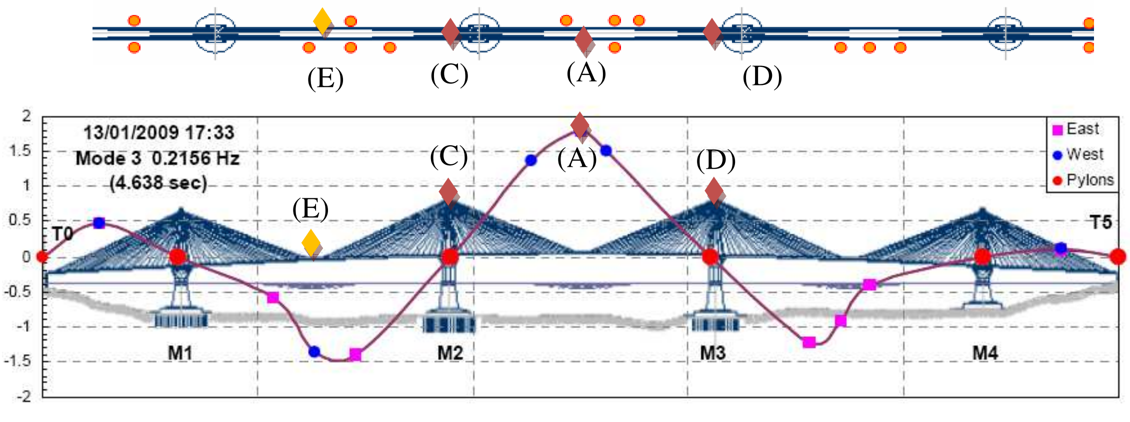

Figure 1: Critical sensors locations and 3rd vertical mode shape of the RION ANTIRION Bridge.

The monitoring system output, apart from alert “over threshold” events consisting of high sampling rate records with minimum duration of 60 sec, initiates regularly (every 2 hours) continuous records of low frequency data (sampling rate every 30 sec). These records were mined over four years in order to extract the vortex shedding occurrences which usually lead to vibration level lower than alert thresholds.

Processing the high sampling rate records, hereafter named "Dynamic files", a number of vortex shedding events corresponding to excitation of the 3rd flexural bending mode (0,216Hz) were revealed, but due to the large record interval (2 hours) compared with the expected event duration, some events were assumed to be undetected. Additionally, even though the maximum amplitude could be reasonably assumed, the total duration of event could not be deduced in order to estimate the number of vibration cycles.

In excess to the analysis of Dynamic files, the peculiar work described in this paper concerns a method developed for processing the low sampling 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 data.

2.2 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 Dynamic files, it was investigated whether the wind force, direction and turbulence were main parameters of alternate eddies excitation or not, over a two years period including 2009 and 2010.

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

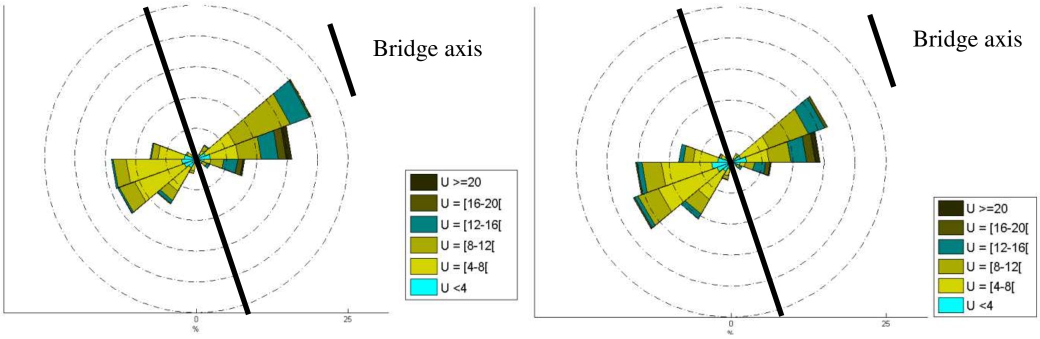

Figure 2: Rose of wind mean speed, M1M2 anemometer, year 2009 & 2010

It was first observed that west wind turbulence was lower than 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 (height of bridge deck) is over 10%. This reference was used for the design process, yielding to consider Iu=12% for the wind model. Full scale data show a turbulence level of 5% or less occuring more than 50% of the time for western winds. This is of particular importance because the vortex shedding excitation strength depends on the turbulence intensity of the wind, the lower the turbulence, the stronger the excitation.

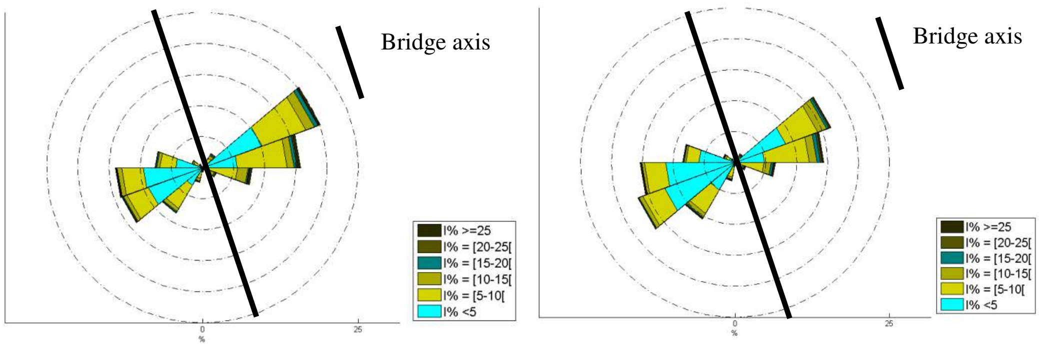

Figure 3: Rose of wind turbulence intensity, M1M2 anemometer, year 2009 & 2010

Figure 4 graphs present respectively the standard deviation (STD) of the acceleration of the deck in the vertical direction, measured at mid span (Deckaccelerometer 17E M2M3E E17E-Z, sensor A of figure 1) versus mean wind speed and versus wind direction (sensor E) for all 2009 monitoring records. Red points on the graphs were identified as 2009 vortex shedding events, due to single mode vibration at a narrow wind range.

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

Same process applied to data from the 2010 monitoring which gave very similar results with 28 vortex shedding events occurring mainly on west wind direction (~255°). The average mean wind speed was 8.5 m/s while the average turbulence level was 2.5 % (0.1-1 Hz bandwidth).

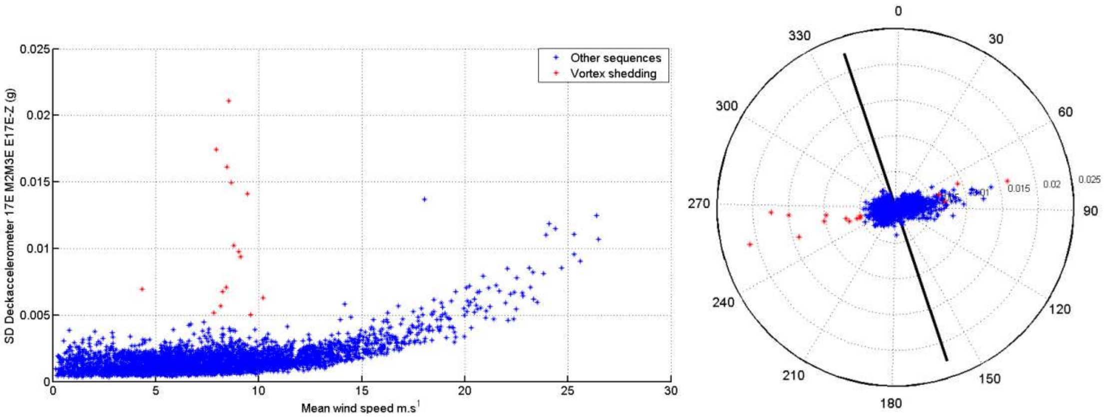

Figure 4: STD Deckaccelerometer 17E M2M3E E17E-Z vs mean wind speed & direction (2009, M2 PXI)

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 5 illustrates a typical example of record of vortex shedding event, where various accelerometers on the deck show sinusoidal signal in phase while pylons on both sides of the deck show opposite sign sinusoidal signal, which is consistent with the modal shape (3rd mode of deck) excited during vortex shedding event.

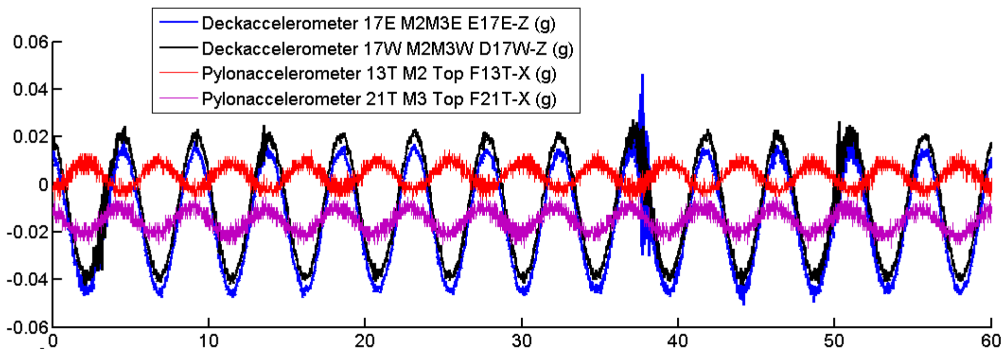

Figure 5: Typical vortex shedding record (m2Dynamic record - 070609 22h00m.txt)

3 Reconstruction of vortex shedding events from Instant records

3.1 Validating the method

As explained previously, the processing of the Dynamic files revealed only 15 events in 2009 and 28 events in 2010 due to records interval. Figure 6 illustrates a “missed” event from Dynamic records. However, these few events can serve as reference for a signal processing analysis using the low sampling (every 30 sec) records titled "Day history" files with the aim to detect and characterize every vortex shedding events (number, duration, maximum displacement). It is reminded that Day history files consist averaged data over 0.5 sec and one value is recorded every 30 sec (sampling frequency 0.0333 Hz) for all sensors.

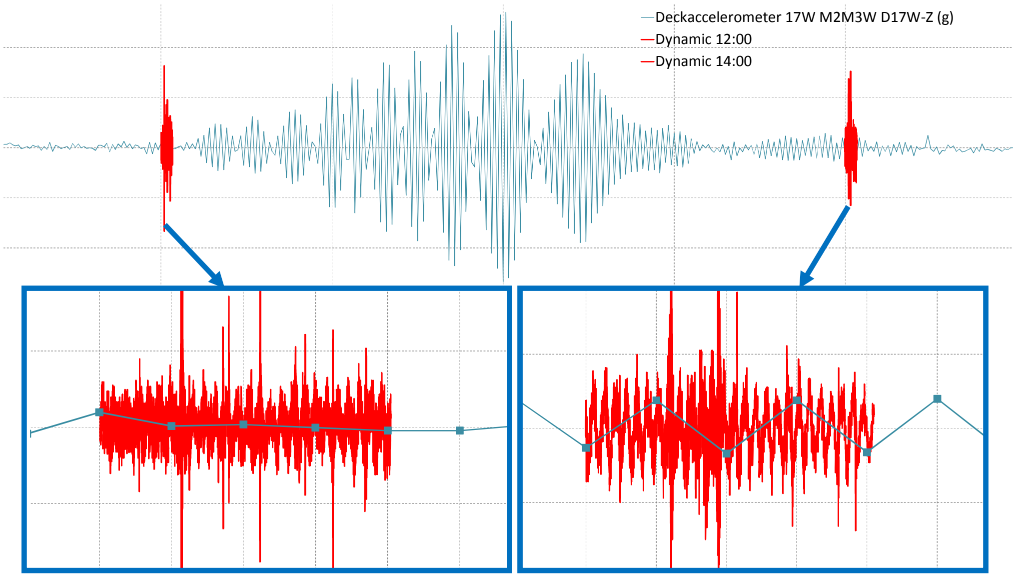

Figure 6: Vortex shedding event occurred between 60 sec “Dynamic files” (2hours interval)

These particular features affect the properties of the recorded signal and they should be investigated in order to interpret the records. The main consequences are:

- Averaging the signal over 0.5s yields to low pass filtering
- Low sampling rate at 0.033Hz yields to aliasing

For the filtering effect, the amplification and the phase information are presented in figure 7 (for dt=0.5 sec averaging), comparing the raw signal V(t) and the averaged (filtered) one $V_A(t)$ regarding amplitude and phase :

$$V_A(t) = \int_{t-dt}^{t} V(\tau) \cdot \frac{d\tau}{dt} \qquad V(t) = A\sin(2\pi f t + \theta) \tag{1}$$

Averaging over 0.5s does not significantly filter any of the modes participating in deck vibration. Especially for the 3rd deck mode (0.216 Hz), the amplification factor is 0.981, and the delay is 0.25 sec. Consequently the vibration of the deck calculated from the day history files and from the instant files will almost have the same amplitude.

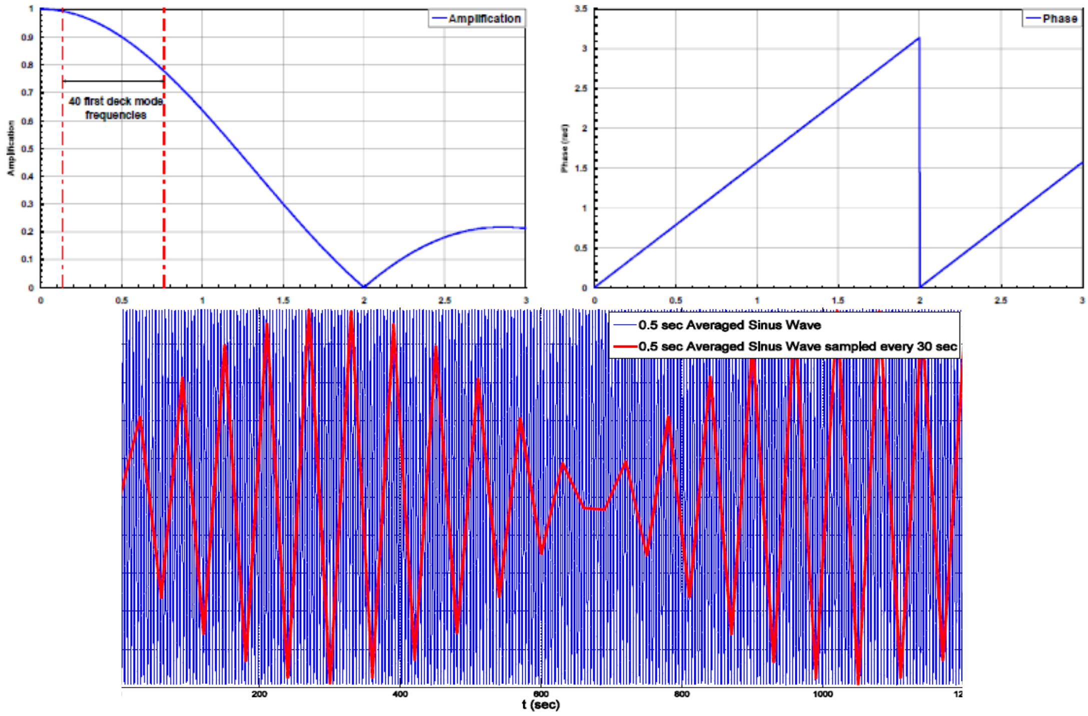

Figure 7: Filtering effect of averaging on amplification and phase shift & Aliasing effect.

Low sampling rate (fs=0.033 Hz) forces every vibration event with frequency fn more than (fs/2=0.0166 Hz) to be represented in an aliased frequency fa.

Aliasing effect is illustrated in figure 7, where a sinus wave (amplitude 1 and frequency 0.216 Hz) contaminated with white noise (noise/signal=0.05) and sampled at 100 Hz is subjected to 0.5 sec averaging and resampled to 30 sec.

The amplitude variation of the aliased signal (red) is due to the fact that the aliased frequency (from 0.216 Hz to 0.016 Hz) is close to the Nyquist frequency (fs/2). If the aliased frequency fn can be rewritten as fa=fs/2-df, the samples Si expressed as

$$S_i = A \cdot \sin(2\pi \frac{f_a}{f_S} i), \tag{2}$$

can be modified to

$$S_i = -A \cdot \cos(2\pi \frac{f_S}{2 \cdot f_S} i) \cdot \sin(2\pi \frac{df}{f_S} i) \tag{3}$$

as a multiplication of a constant amplitude wave with frequency fs/2 with a very slow wave with frequency df. In this case the slow wave has a frequency 1/60-0.016=0.00066 Hz (1500 sec period).

For each value of original “History” record with sampling frequency Facq, 2 different type of subsamples (time window) were selected, a centered one, and a backward shifted with N values duration (size of time window). For each subsample, the Standard deviation was calculated as an index of vibration amplitude. The standard deviation of a subsample is defined by:

$$\text{STDssamp(t)} = \sqrt{\frac{1}{\text{N - 1}} \sum_{i=1}^{N} (x_i - \bar{x}_N)^2} \tag{4}$$

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

$$x_N(t) = \left\{ \frac{x(t - \frac{N}{2 \cdot f_{acq}}),.., x(t + \frac{N}{2 \cdot f_{acq}})\_(centered)}{x(t),.., x(t + \frac{N}{f_{acq}})\_(shifted\_backward)} \right\} \tag{5}$$

Both methods were compared for occurrences when Dynamic files have been recorded and can serve as "reference". Figure 8 shows that the centred method induced less time shift in the time localization of the maximum of amplitude than the backward method. Therefore the centred method was preferred even if the determination of amplitude was no so accurate.

The size of the calculation window was optimized too by comparing the value of RMS of a Dynamic file with STD of “History” records. As shown on figure 8 a 5-minute window was found best fitting the results from Dynamic files with a correlation between STD calculated by the two methods of 90% to 95%. This optimization is a balance between a reduced number of data (5-minute 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).

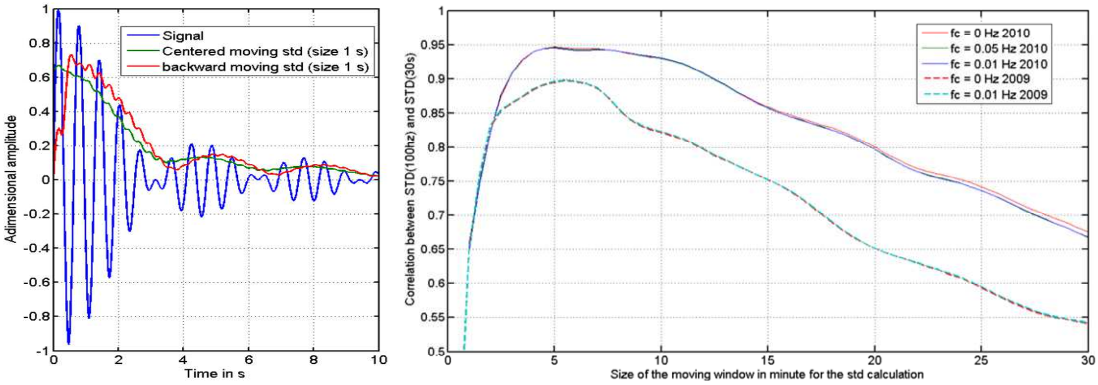

Figure 8 : Comparison of centered and backward subsamples and time window optimization

After optimizing STD calculation parameters on the “History” records, a final correction factor, occurred from the correlation with the RMS values of each “Dynamic” record that captures a vortex shedding event. This correction factor took a value of 0.893 in this case.

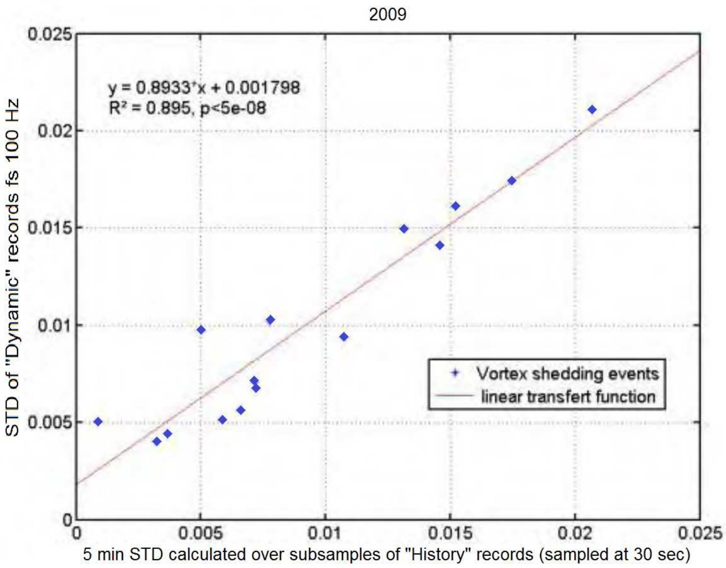

Figure 9: Correlation between STD calculated from “Dynamic” records and STD calculated from a time window of “History” records

For application of current methodology to different structure with different properties, the whole process, first the optimized window length for calculation of STD, and then to the correction factor between the “real” STD value and the one issued from the low sampled records should be repeated.

3.2 Applying the method over 5 years data files

Finally, occurrences of vortex shedding events were reconstructed over years 2006 to 2010 (5 years) and showed that many short duration events had not been detected by the standard monitoring process. For instance for year 2010 the number of vortex shedding events detected by the processing of the Day history files is 144, when only 28 events had been evidenced when processing the Dynamic files.

For each occurrence of an excitation due to vortex shedding, both the duration of the event and the max amplitude reached have been computed.

For the calculation of fatigue of the structural elements it was conservatively considered that the maximum amplitude was applied in a number of cycles deduced from the event duration multiplied by the frequency of the 3rd flexural mode. A table of loads has been filled for each stay with the summation of all cycles related to all event of the same year. The five years load tables are combined in one unique table and multiplied the figures in boxes of this load table by 24, a load table for a period of 120 years (bridge service life) was obtained that was used for checking the risk of fatigue on each cable's anchorage. This process finally ended to the conclusion there was no risk of fatigue due to the accumulated effect of loads induced by the vortex shedding excitations of the deck.

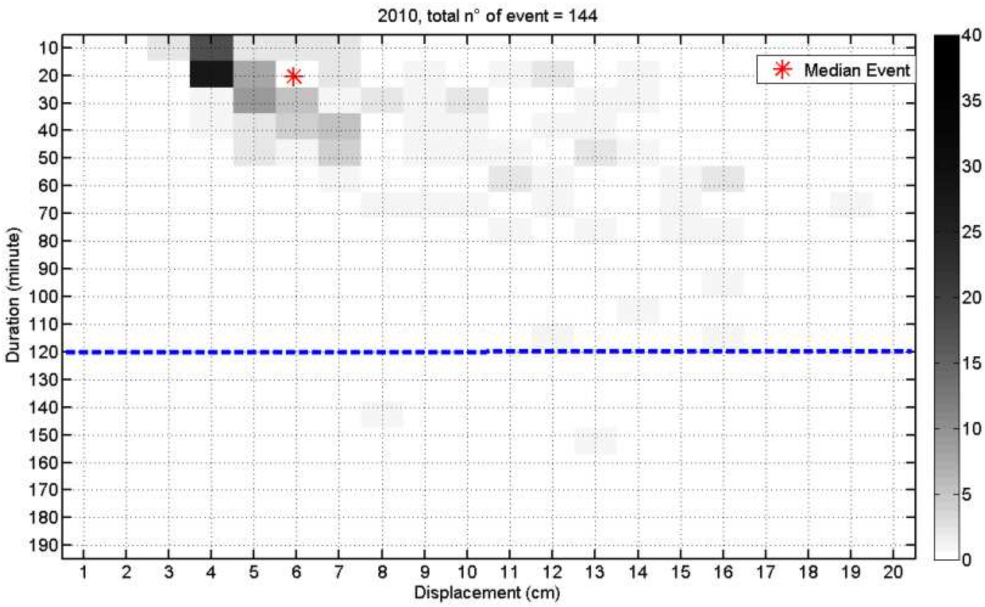

Figure 10: Table of reconstructed vortex shedding events for the year 2010

CONCLUSION

Current analysis indicates the possibility to obtain crucial and complete information of particular structural response, such as deck excitation due to vortex shedding, without requiring an enormous database of high frequency records.

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