GEODETIC MONITORING OF BRIDGE OSCILLATIONS

EVANGELIA LAMBROU, GEORGE PANTAZIS

National Technical University of Athens, School of Rural and Surveying Engineering, Greece
e-mail: litsal@central.ntua.gr, gpanta@central.ntua.gr

ABSTRACT: A total geodetic methodology is being presented for the simultaneous real-time monitoring of two or more points on a given bridge. The methodology is based on the **synchronization of two high accuracy and dexterous total stations**. The application was carried out on the Halkida Bridge. The geospatial data is presented in time series. In addition, the determination of the main frequency of oscillation was calculated by using the FFT analysis.

KEY WORDS: Bridge; total station; synchronization; simultaneous real-time monitoring; Halkida; oscillation

1 INTRODUCTION

The gigantic technical and industrial structures that have been built in recent decades such as big bridges, silos and dams need continuous monitoring of their dynamic behavior during their operation.

The monitoring of the dynamic oscillation and the deformation of any certain bridge, constitute today one of the most interesting subjects of study. Through these studies, external factors and their influence on the operation of a bridge have become familiar to scientists and have given them the insight for better constructions. The goal of a ″bridge’s monitoring″ is for the determination of:

- The bearing ability of a bridge’s body
- The deformations and the payload of specific cross sections
- The resilience of the construction materials
- The change of the temperature or the augmentation of the humidity

The monitoring of these phenomena may be carried-out simply by using systems of geotechnical instruments. The measurements made by geotechnical instruments are quite accurate of the order of ±0.1mm and their measurements are direct and continuous. But these measurements are uncorrelated to each other, as they don’t refer to the same reference system and provide only quantity information. Furthermore, their credibility depends on the proper operation of the instruments.

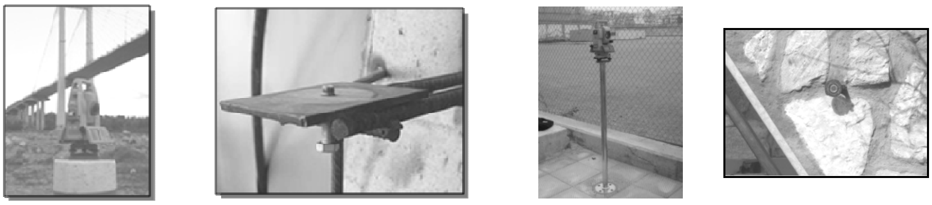
Today, this type of monitoring can be totally supported by using geodetic instrumentation and methodology. The evolution of the geodetic total stations and GPS receivers has maximized their contribution to bridge deformation and oscillation monitoring with adequate accuracy.
The main advantages of using the geodetic methods are as follows:

- The measurements are correlated to each other.
- The coordinates of the selected points are referred to a unique reference system.
- The use of a network adjustment.
- The determination of the absolute and relative movements between the selected points.
- The evaluation of the results is carried out for a specific confidence level, according to the user.
- There are qualitative and quantitative results.
- The geodetic measurements can also be adjusted with the geotechnical ones in an entire adjustment.

2 GEODETIC MONITORING METHODS

The geodetic methods that are used for monitoring purposes, utilize conventional (terrestrial) or satellite instrumentation. These methods are applied by establishing continuous and/or repeated measurements at regular time intervals of a 3D network.
This monitoring is realized by using robotic total stations [5], [7] or receivers of the satellite positioning system. The points of the network are established on the bridge’s body and on the surrounding area of any stable ground.
Special care must be paid to the means used for the establishment of a network points. The selection of these points must ensure their stability at the place set, in time and the unique set up of the instrument. Also, the unique sighting of the targets at every campaign of the measurements is very important. As the final uncertainty of the calculated coordinates and the calculated displacements mainly depends on the above mentioned parameters, therefore, special designed constructions are used:

- pillars with a metal head on their top, which bears the appropriate screw for the placement of the selected instruments (photo 1a)
- Permanent plates in the ground with mobile poles to support the instruments (photo 1c).
- Permanent plates, with the appropriate projection screw, which can be placed on vertical walls of a bridge’s body (photo 1b).
- Mini reflectors, which have been permanently positioned on the bridge’s body for accurate targeting and distance measurements (photo 1d).



(a) (b) (c) (d)

Photo 1. Means for realization of the network's points

Once the appropriate adjustment of the network has been achieved, either by using terrestrial or satellite measurements, the coordinates of the network's points are calculated as well as their uncertainties for every campaign of measurement. Moreover, the absolute and relative displacement of each point is computed for a selected confidence level. Thus, the simultaneous 4D (3D and time) determination of the change of position of each point is feasible by an accuracy, which fluctuates between a few mm to a few centimetres. Additionally, the time series of the oscillation of each point can be drawn.

As far as the advanced modern total stations are concerned, those are used in these applications:

- They have servo electric or piezoelectric movement. They can turn from phase I to phase II in about 2 sec. That means that they can monitor a target with an angular speed of 200m/sec at 100m.
- They can automatically recognize a target without human assistance (ATR). Thus, they can take the measurement, by self targeting and without the need of an observer. Hence, eliminating the systematic error that is caused by a human's sighting.
- They can lock on a target and take a measurement at specific time interval as the user defines. The maximum operation frequency is 10Hz depending on the environmental conditions as the mean operation frequency is about 4Hz.
- Their angle measurement accuracy reaches ±0.5″, their distance measurement accuracy ±0.6mm±1ppm and they reach an accuracy of ±3mm when tracking a target. Thus, the uncertainty of the determined coordinates of each point can be of the order of few millimeters.
- Results can be sent in real time to a connected PC at the field or to the office PC, as they support internet connection.
- They register simultaneously the 4^{th} dimension, which is the time of the observation, by an accuracy of ±0.01sec or more. The registered time used could be set at any given time or at the original Universal Coordinated Time (UTC) [10] as the GPS receiver registers. This possibility is available thanks to the credible embodied chronometer that they have. In addition, their operation in Windows CE interface permits their synchronization to the UTC time, directly via internet connection, by using the appropriate time server.

Otherwise, the ActiveSync software is used on a PC in order to communicate with the total station. During this communication the PC time is transferred to the total station. The time of the PC could be set at any given time or the PC could be pre- synchronized via the internet by using a worldwide time server [12], which has an accuracy of ±0.001sec.

A total station connection to a PC could be carried out, either by a USB cable or a wireless connection by Bluetooth. The synchronization of the total station with the UTC time is essential and important as, in this way, measurements and results can be compared with others, which could be gathered simultaneously by GPS or by using geotechnical instruments.

As far as the GPS receivers that are used for these applications are concerned:

- They must be double frequency receivers for more accurate results.
- An advanced choke ring antenna must be used.
- They have the opportunity to register measurements in high frequencies 10 - 20Hz [8]. This helps the monitoring of bridges as well as springy constructions, antennas and high buildings such as sky scrapers.
- The accuracy of the calculated coordinates is of the order of some centimeters.

A great disadvantage of using a GPS in such monitoring tasks is that the bridge is a very unfriendly environment for GPS antennas. Many multipaths in the GPS signal are caused, due to the metal structure of the bridge's body, the movement of the vehicles, the passing of the pedestrians, the reflection of the water's surface, the weight of the antenna and its own oscillations caused due to the wind. All the above mentioned parameters cause an error which can reach 10cm, even if choke ring antennas are used [6].

The above instrumentation can be also used together. The measurements can be adjusted together for several phases.

As both kinds of instruments and methods provide the monitoring in 4 dimensions, the automatic measurements of at least 4Hz and the independence of the measurement from the observer and his/her personal errors then the major benefits of the use of a total station vice GPS are:

- It provides more accurate results so the network is more sensitive to the determination of movements or oscillations.
- It provides reliable measurements as it is influenced at a minimum by the environment.
- It allows for the possibility to install the network's point on any given position on the bridge's body, even on "difficult positions", where a GPS's antenna cannot be placed. Such as:
    - where there is no sky view and the satellite signal is relatively impossible or problematic.
    - where The GPS's antenna receives many multipath signals due to the above mentioned parameters.

There have been many applications made worldwide for a bridge's monitoring. As in the case of the old bridge of Arta in 1983, in Greece, by using terrestrial methods, the Humber Bridge [1], the suspension of the Forth Road Bridge in Scotland, [4] by using GPS receivers, the Halkida Cable Bridge in Greece, by using both a total station and a GPS receiver [2], [9] and the Gorgopotamos Bridge in Greece [3].

3. Simultaneous and real time monitoring by using total stations

The aim of the proposed methodology is the monitoring possibility of a bridge oscillations at two difficult and yet different positions on its body, by using total stations during continuous traffic. The main purpose is for the position of each target to be registered in space and time and to be comparable to each other.

Two instruments should be used, a-priori synchronized to each other and/or with the universal time UTC. They will monitor simultaneously two different targets (reflectors), which have been mounted on specified positions on the bridge's body. Thus, the oscillation time series for each target can be drawn. The comparison of the corresponding time series of each target will give the differential oscillation between the points at the same time.

An experiment of this kind was carried out on Halkida's cable-stayed high Bridge, in Greece. A permanent network was established in the surrounding area for the bridge's monitoring. The network consisted of 6 beton pillars, which were installed in the surrounding area and about 50 retro reflectors, which were stabilized on specified positions on the bridge's body.

Two advanced total stations were used. The Trimble VX and the Topcon IS. Both provided angular accuracy of ±1″ or ±0.3mgon as their distance measurement accuracy was ±3mm±2ppm and ±2mm±2ppm, respectively. They operated in Windows CE interface and they registered their measurements automatically by frequency of 1Hz and 4Hz, respectively.

Prior to their use, both instruments were connected to a PC and they were simultaneously synchronized to the UTC time, using the same server.

However, a few days earlier the drift of their time keepers had been calculated for some days. It was found that their clocks had a delay, which was less than a second within the two-day time period that they were checked. So, from this it was gathered that if they were synchronized just before the measurements, then the time correction for the following few hours would be insignificant. The measurements were registered by 1Hz frequency for 15 minutes for each experiment.

Two different experiments were carried out. In the first one we had to verify the simultaneous of the registration and the instruments' credibility. Thus, both instruments were monitoring the same omni direction prism, which was situated at the middle of the bridge, between the two main pillars of the bridge (fig. 1).

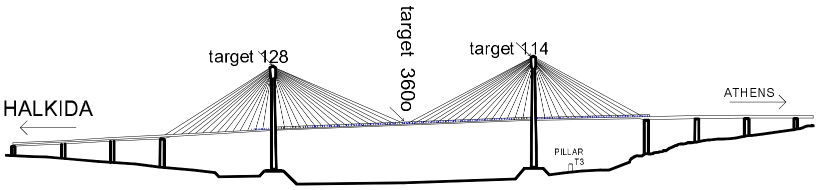


Figure 1. The Halkida bridge and the monitoring locations

Figures 2, 3 illustrate the time series for the y and z coordinates, respectively. The fine line is the registration of the VX station as the bold one is the registration of the IS. The diagrams show that both instruments give the same result at the same time. Some small differences that appeared were within the expected uncertainty of the measurements.

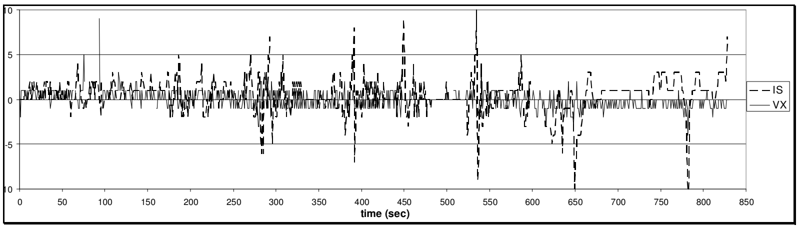


Figure 2. Time series of the cross-section displacement

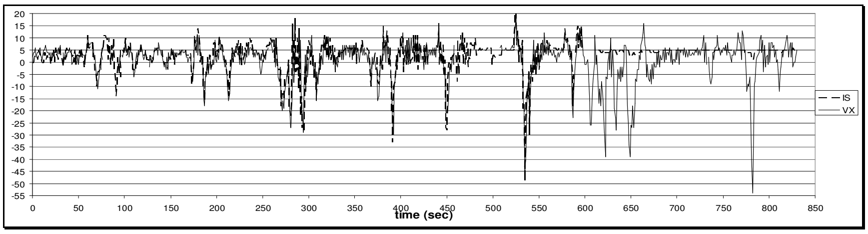


Figure 3. Time series of the vertical displacement

In the second experiment each total station monitored a different target. The reflector-targets were situated at the highest point of the two main pillars of the bridge (fig.1). The goal was to observe the oscillation frequency differences between these points caused by the same traffic. Figures 4, 5 illustrate the time series.

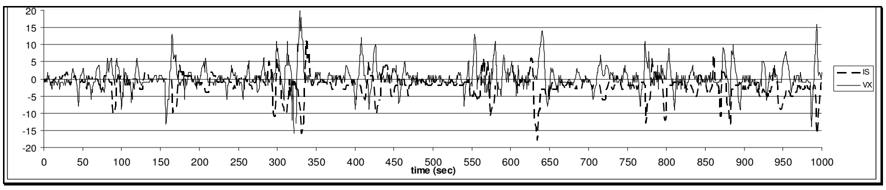


Figure 4. Time series of the cross-section displacement

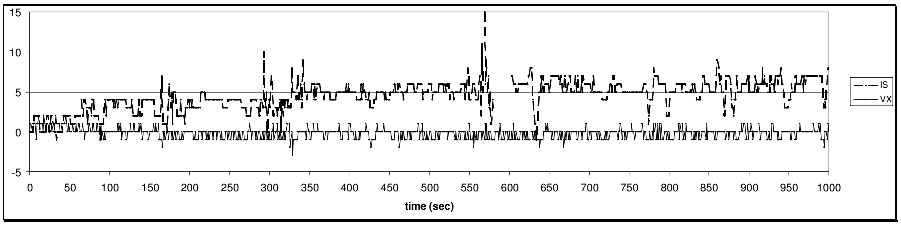


Figure 5. Time series of the vertical displacement

The coordinates of the points were calculated by the total station software in real-time and the time series were drawn-up by a laptop, which was connected to the station. The accuracy of the coordinates was estimated at ±3mm.

Additionally, a spectral analysis FFT was carried out where the frequencies of the oscillations were calculated. Figures 6, 7, 8 and 9 present the frequencies of the vertical direction in both experiments. The main frequency that was calculated for each case using the Lomb method [11], was about 0.4Hz. This is within the bridge’s construction study.

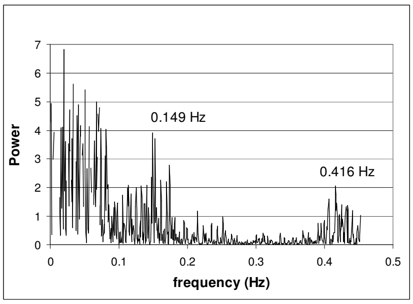


Figure 6 . Spectral analysis of vertical displacement for VX (first experiment)

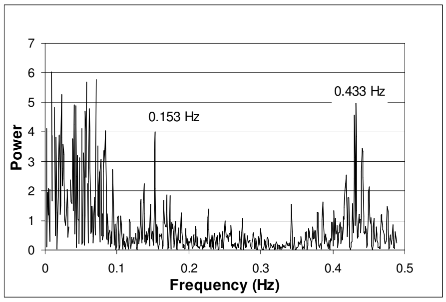


Figure 7. Spectral analysis of vertical displacement for IS (first experiment)

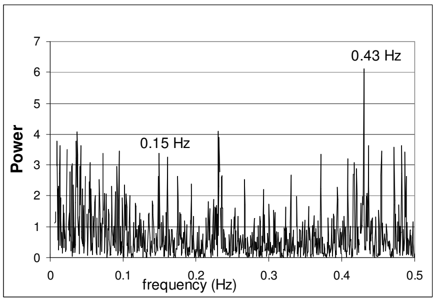


Figure 8. Spectral analysis of vertical displacement for VX (second experiment)

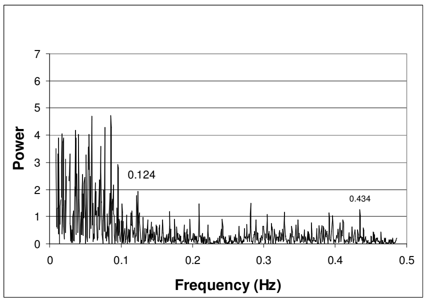


Figure 9. Spectral analysis of vertical displacement for IS (second experiment)

4 CONCLUSIONS

The bridge's oscillation monitoring is of great importance for the scientific community. The GPS monitoring doesn't prove to be adequate, due to the random errors, which are increased by the environment and the existing materials. The advanced total stations seem to be an alternative solution to this problem as they provide considerable accuracy. Although their registration frequency is smaller than the GPS receivers their results have credibility.

The experiments that were carried-out show that the main frequency of a bridge's oscillation can be calculated even with registrations of 1Hz frequency. It is reminded that today, the registration can be achieved with 7-10Hz by newer total stations.

Furthermore, the registration of an accurate time as well as the opportunity of synchronization to the UTC time, gives scientists the possibility to combine their measurements with a GPS's measurements or a geotechnical instruments data.

It is also worth mentioning, how remarkable it is that we now have the opportunity to monitor targets in difficult or covered points.

Finally, the establishment of such targets is cheaper than the establishment of GPS antennas, not to mention more easily attainable and safer as the weather conditions don't influence them.

It could be then concluded, that the use of an advanced total station in the monitoring of a bridge is more advantageous than that of a GPS.

The disadvantage of the slow registration (1-4Hz) that these total stations provide today is expected to be surmounted in the years to come, making them more robust.

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