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A REAL-TIME INSTRUMENTATION APPROACH FOR STRUCTURAL HEALTH MONITORING OF BRIDGES

S. Dinçer[1], E. Aydın[2] and H. Gencer[3]

ABSTRACT

Among all civil engineering structures, bridges & tunnels are two of the leading types that should be monitored by sensors due to their critical fatigue and creep behavior. Especially natural events such as earthquakes, floods, storms increase the importance of monitoring. A number of different types of instruments and sensors should be combined in health monitoring of railway/highway bridges, tunnels, tube crossings and subways. Although customization has a big importance in a specific health monitoring instrumentation project of a bridge or tunnel, accelerometers, strain/crack gauges, tilt, wind and temperature sensors are the most generally preferred sensors.
Accelerometers are used for operational modal analysis, which reveals 2 important issues about the health of the structure. First, the real modal frequencies measured from the real structure shows how close it behaves in parallel with its design project. Secondly whether this characteristic behavior changes in time or after a specific event indicating a potential damage in the structure.
Similarly, strain/crack gauges provide direct information about the deformations along the bridge. This is important for realizing excessive unexpected deformations and locating the neutral axis. Furthermore strain gauges directly monitors the dead loads along the structure measured in specific cross-sections in a tunnel.
TESTBOX™ / eQUAKE™ series DAQs provide different solution opportunities for different projects needs. In this study key, parameters affecting an instrumentation project are explained in detail. Furthermore, wireless/wired monitoring, different sensor sensitivities, real-time or short-term monitoring are discussed. The discussion is extended to combining dynamic and static measurements. A robust alternative from fiber optic sensors are also included in the study strengthening the solution. In this way, a turn-key and integrated approach for real-time structural health monitoring of bridges & tunnels is presented.

Keywords Real-Time Structural Health Monitoring • Bridge Monitoring • Operational Modal Analysis • Wireless GPS Synchronization • Ultra Low Noise Accelerometer • Strain Gauge • Simultaneous Sampling • 24 Bit Data Acquisition

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A Real-Time Instrumentation Approach for Structural Health Monitoring of Bridges

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ABSTRACT

Bridges & tunnels are the two leading types of structures that should be monitored by sensors due to their critical fatigue and creep behavior. A number of different types of instruments and sensors should be combined in health monitoring of railway/highway bridges, tunnels, tube crossings and subways. Accelerometers, strain/crack gauges, tilt, wind and temperature sensors are the most generally preferred sensors. Accelerometers are used for operational modal analysis, which reveals 2 important issues about the health of the structure. First, the real modal frequencies measured from the real structure shows how close it behaves in parallel with its design project. Secondly whether this characteristic behavior changes in time or after a specific event indicating a potential damage in the structure. Similarly, strain/crack gauges provide direct information about the deformations along the bridge. This is important for realizing excessive unexpected deformations and locating the neutral axis. Furthermore strain gauges directly monitors the dead loads along the structure measured in specific cross-sections in a tunnel. TESTBOX™ / eQUAKE™ series DAQs provide different solution opportunities for different project needs. 7/24 real-time monitoring, wireless/wired monitoring opportunities, different sensor sensitivities are discussed in this study. The discussion is extended to combining dynamic and static measurements. A robust alternative from fiber optic sensors are also suggested in the study strengthening the solution. In this way, a well-combined (dynamic-static) and integrated approach for real-time structural health monitoring of bridges & tunnels is proposed.

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Introduction

History of civil engineering is full of examples of sudden and unexpected failures of bridges and tunnels. Only two examples of this disastrous collapses are shown in Fig. 1. One is from 1940, Tacoma Narrows Bridge collapse (on the left), and the other one is a very recent disaster in Çaycuma, Turkey, in year 2012(on the right). Tacoma Bridge collapsed less than 1 year after its construction, and the bridge in Çaycuma was 61 years old when it collapsed. The reason for the collapse of these bridges are still being discussed. At least 3 theories are still available for the collapse of Tacoma Bridge, and neither one has been agreed on yet.

Bridges are generally designed to carry vehicle traffic. Due to this natural design philosophy, they are exposed to intensive and continuous dynamic loading during their lifetime. Naturally, a fatigue behavior should generally be expected for a bridge. Nakazawa et al. conducted an experimental study on 2 aged reinforced concrete bridges, and showed that aging caused reduction of rigidity for these bridges.[1] Similarly tunnels are exposed to huge static loads during their lifetime, again due to their design nature. For tunnels creep behavior may be considered as a more common cause of failure.

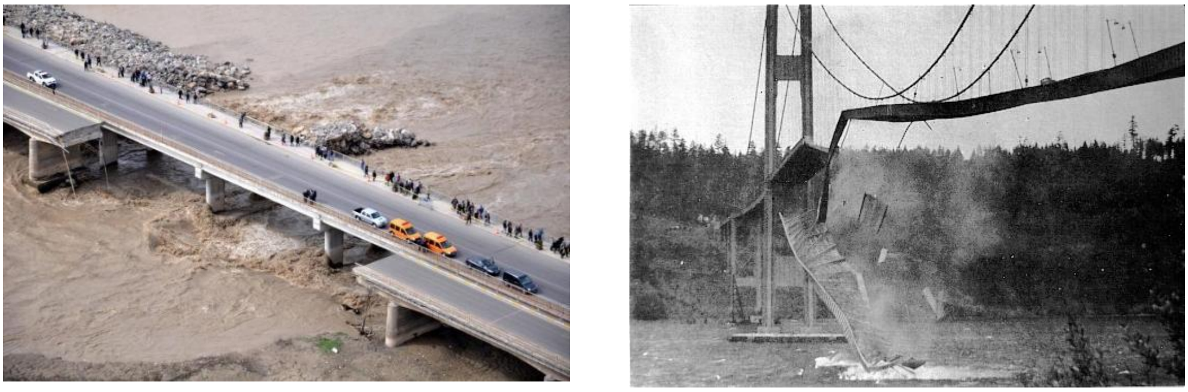

Figure 1. Two examples of disastrous bridge collapses. Right-Çaycuma, Turkey, 2012. Left-Tacoma Narrows Bridge, 1940.

Structural health monitoring of bridges and tunnels always attracted attention of engineers and administrators of these structures. Since these structures always includes a potential risk of sudden failure, monitoring them is important for providing the necessary time for taking precautions and not facing the unexpected disasters. A second important result of monitoring is to get real data to understand the phenomenon and conduct research studies and modify future designs accordingly. Two detailed and well categorized studies on this area are, Study and Application of Modern Bridge Monitoring Techniques [2] and Lessons Learned in Structural Health Monitoring of Bridges Using Advanced Sensor Technology[3].

In parallel with the technological developments, it is possible to apply much precise sensors and systems for a considerably less cost. Developments in MEMS (microelectromechanical systems) technology, digitizers, data transfer lines and options, and fiber optic sensor technology are all the main components of these more reachable and more efficient monitoring possibilities. This situation causes the electronics and instrumentation technology to intersect with Civil Engineering discipline. At this point of intersection, designing a correct monitoring system by selecting the right instruments among a big batch of alternatives becomes more important.

The scope of this study is focusing on the instrumentation part of the structural health monitoring for bridges and tunnels, rather than discussing the results of the analysis from structural engineering point of view.

7/24 Real Time Monitoring

All the instrumentation proposed in this study is based on 7/24 real time monitoring. Fig. 2 shows the general flowchart of the suggested approach. Suitable types and numbers of the sensors and should be decided individually regarding the design of the bridge and the main target of the monitoring project. However, two main types of sensors are used in general in each monitoring project, static and dynamic. The instrumentation approach in this study suggests an Ethernet compatible data line for the dynamic measurements and fiber optic sensor line for the static measurements. The reasons and details of this suggestion is given at the following sections.

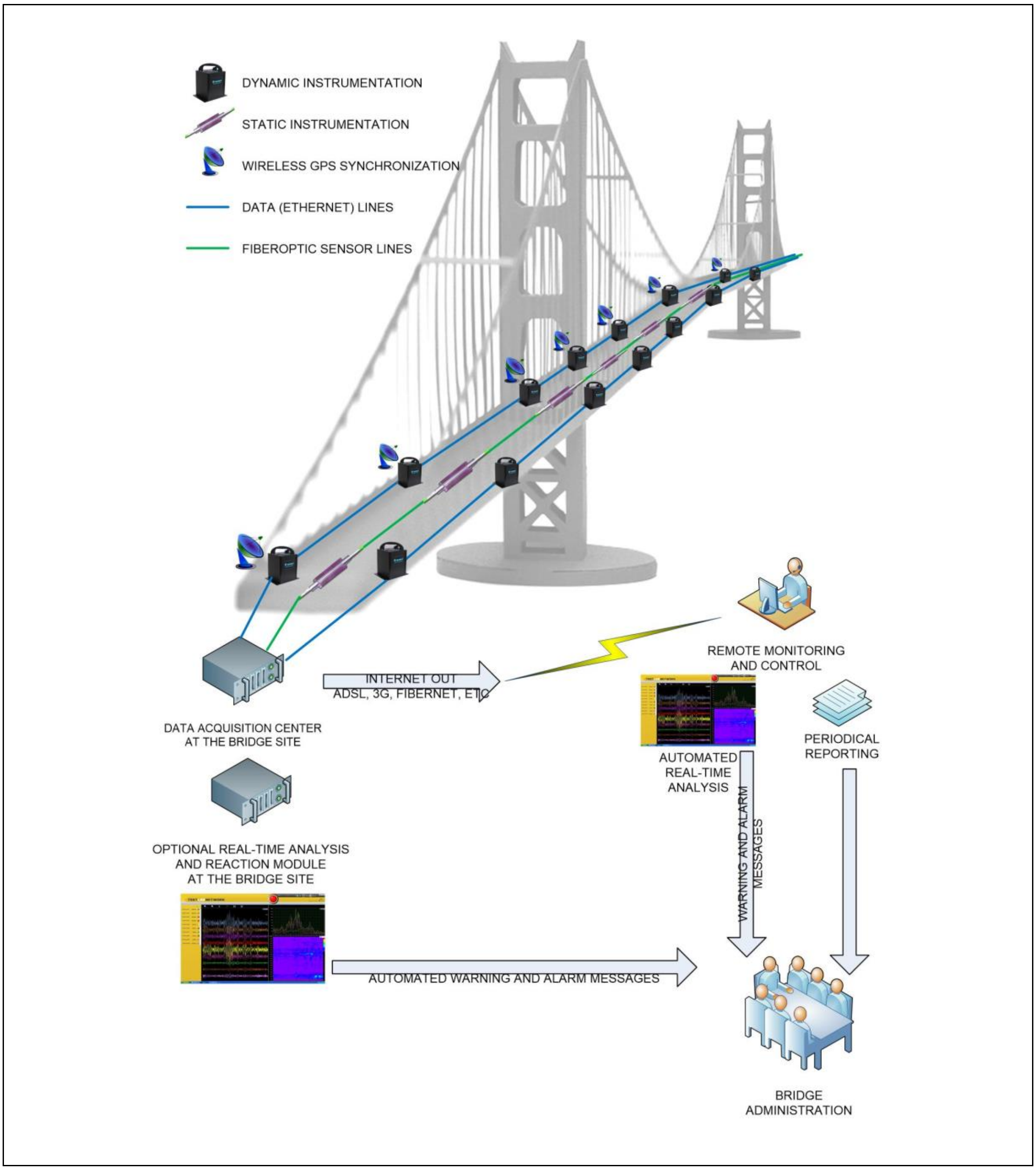

Figure 2. The general diagram of the suggested 7/24 real-time instrumentation approach.

Both static and dynamic data lines are connected to the main data acquisition center at the bridge site. This data center works on 7/24- 365 days a year principle and is at least capable of acquiring all the data together, synchronizing and transferring it to any remote location over an internet gateway. The data center has the capability of recording the data locally, based on preset trigger conditions, as well.

All the data incoming from the sensors located at the bridge is monitored continuously at one or more than one remote locations. A real-time and continuous, software based analysis is carried out at the remote monitoring center. This software based real-time analysis works as a decision support system for the administrators and engineers at charge. Warning messages are reported to the bridge administration immediately. More than this, periodical structural health reports are prepared and presented based on the mid/long-term changes of the structural behavior. It is also possible to prepare structural health reports after events such as major, earthquakes, storms or floods.

A real-time analysis and reaction module is optional for the bridge site, which should be planned with great attention and care. If this module is installed at the site, a real-time and continuous analysis is carried out at the bridge site. Any possible instabilities resulting from this analysis is reported to the bridge administration immediately. Another function of this module is starting different levels of preset alarm and reaction scenarios at the bridge. The possible scenarios maybe preventing further approach of the traffic to the bridge, or starting audio visual warnings for the people, to inform them to abandon the bridge shortly. Certainly the scenarios should be decided by the bridge administration carefully, and a detailed study should be carried out for linking the module outputs to the automation system of the bridge.

Dynamic Instrumentation and Monitoring

According to the instrumentation approach proposed in this study both dynamic and static measurements should be taken from the bridge for a healthy structural monitoring process. Dynamic measurements are primarily based on accelerometers. The main purpose is monitoring the dynamic behavior of the bridge. In this way it is possible to carry out an operational modal analysis study of the bridge. Although a detailed modal analysis study should be carried out as a post process, it is possible to analyze some important values such as natural frequency and vertical displacements at real time, automatically, by the online analysis software. A solid example of post process modal analysis and damage detection study has been carried out by Brincker et al. on Z24 Highway Bridge [4]. ARTEMIS™ Modal Analysis tool has been used at this study. It is possible to find many similar modal analysis studies for bridges.

Accelerometer Selection (for Operational Modal Analysis)

Before discussing the selection criteria for the correct accelerometer, ambient vibration vs. forced vibration testing and modal analysis should be explained. In forced vibration testing a well-defined action is applied on the structure. This force is generally comparably in higher amplitudes and the reactions can easily be measured even by low-resolution accelerometers. However, in 7/24 monitoring it is not possible to apply well-defined forces on the structure continuously. Instead a simpler methodology is preferred. Operational modal analysis under ambient vibration. The structures are continuously excited by ambient vibrations, such as wind, or little seismic movements. For a structure like bridge, the traffic load itself (such as a train or truck passing through) creates a higher amplitude excitation on the structure.

This ambient vibration is assumed to be very close to a white noise. A typical and ideal white noise in presented in Fig. 3. As it can be seen from the figure although the time domain do not reveal much about the characteristic of the excitation, no specific peak frequency is observed in the frequency domain, a Gaussian distribution can be followed at the histogram. As the excitation is assumed to be close to a white noise, in ambient vibration tests, the modal analysis is carried out depending only on the measured reactions of the structure and therefore it is called an output-only modal analysis, which simplifies the measurement stage.

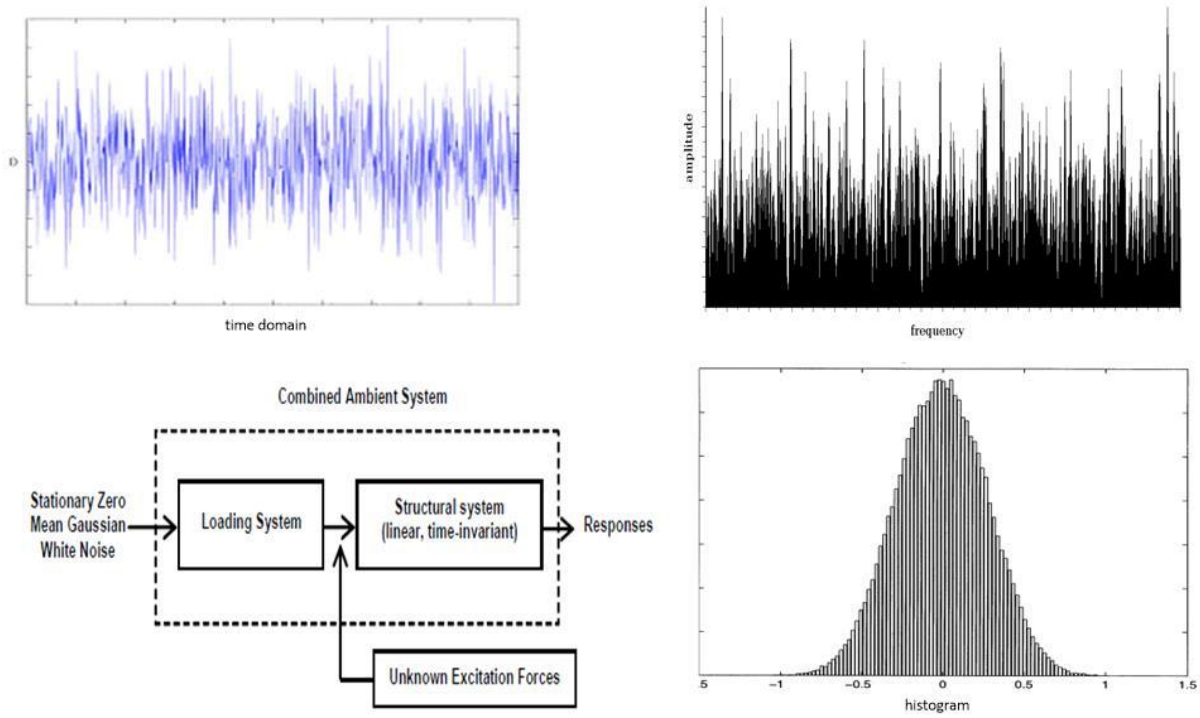

Figure 3. Operational modal analysis (output only), white noise excitation.

Anyhow, this simplification is only possible with the correct choice of both the accelerometers and the digitizers (sometimes also called as data acquisition systems).

If a dynamic analysis will be carried out under ambient vibration, a general rule of thumb is selecting 24-bit, simultaneous sampling digitizers which at least have 120 dB dynamic range combined with ultra-low noise accelerometers which at most have ±3g input range. However, even with these guidelines in hand, the selection sometimes can still be confusing.

For the accelerometers, good matches can be listed as FBAs(force balance accelerometers), ultra low noise MEMS(microelectromechanical sensors), METs(molecular electronic transducers) and IEPE type piezo accelerometers.

-Conventional FBAs: best for long period signals, close to DC.
-MEMS/METs: also including force-feedback, best for 0.1 to 100 Hz signals.
-IEPE type piezo-electric: best for high frequency measurement

A cost - performance chart of low-noise, high precision, low frequency accelerometers are presented in Fig. 4. In general, correctly selected MEMS/MET sensors provide enough performance at considerably lower costs for ambient vibration studies. These types of sensors are often used in dynamic monitoring of bridges. A monitoring study conducted on Golden Gate Bridge is one of the solid examples for the use of MEMS sensors in bridge monitoring. [5]

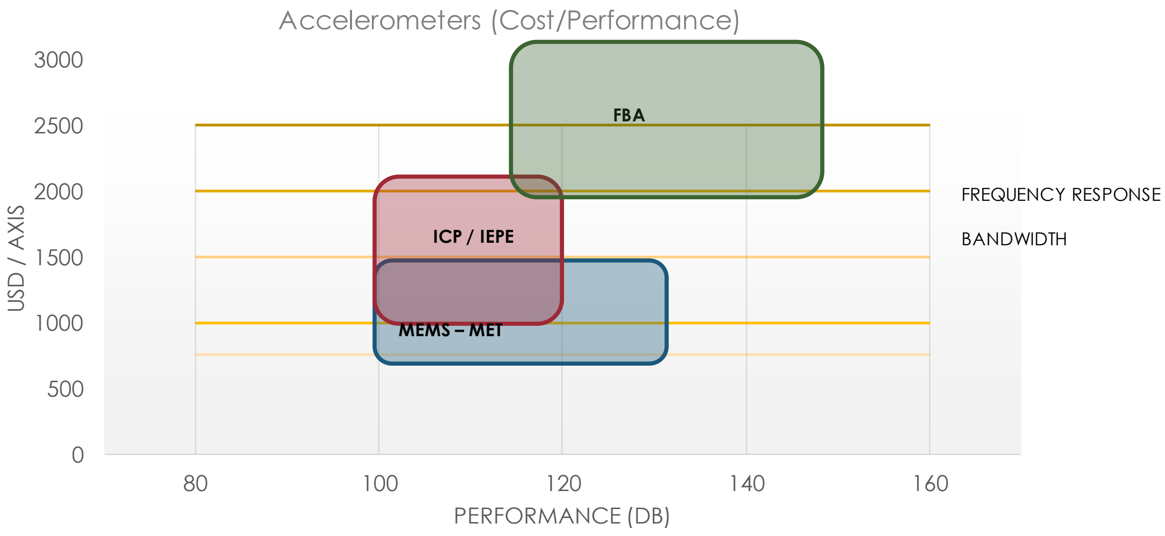

Figure 4. Cost-performance chart of high precision, low frequency accelerometers.

The RMS noise density may be the most important parameter at the selection of the correct accelerometer. A value lower than 10µg/√Hz down to 300nano-g/√Hz is generally acceptable. However, this is still a large range for the selection. Roughly it is possible to say 300-500 nano-g/√Hz is essential for relatively rigid structures such as buildings. Meanwhile, about 5µg/√Hz is generally acceptable for a bridge.

Digitizer Selection

In this study, a series of combined accelerometers and digitizers are preferred for the proposed solution. These combined devices should include 5µg/√Hz or 150nano-g/√Hz accelerometers inside, and produce a direct digital output that can easily be transferred digitally over ethernet line or any other data line. 100-200 Hz sampling speed per channel will be enough to analyze lower structural frequencies.

Full wireless data transfer will be a potential problem cause for a permanent monitoring system on a bridge, due to communication failures. On the other hand, using one central multi-channel digitizer, and connecting the accelerometers to the device with analog cables will create 2 potential problems. First one is the electrical noise and signal loss on analog cables especially in long span bridges. And the second one is the difficulties in and cost of analog cabling compared to digital cabling. So, the third way, which is, digitizing the analog data locally at measuring locations and transferring the digital data with cables seems to be the best alternative.

The preferred devices should also have local storage capability for temporary communication failures. The most important feature of this solution is that, the digitizers should have a synchronization method between them in order to provide suitable data for the modal analysis, although located separately from each other.

TESTBOX™/e-QUAKE™ series devices are one of the best fits for the dynamic part of the health monitoring instrumentation of bridges. This series also provide different solution opportunities for different monitoring projects. TESTBOX™/e-QUAKE™ series have already been used in the health assessment of a number of steel and concrete bridges.[6],[7],[8],[9].

GPS Based Wireless Solutions

As stated in the previous section, the digitizers should have a synchronization method between them in order to provide suitable data for the modal analysis, although located separately from each other. One way of providing this synchronization is using a GPS module on each digitizer. In this way, all the digitizers will perform the analog to digital conversions being synchronized at 1 micro-second resolution of UTC. The special solution of TESTBOX™/e-QUAKE™ series devices for synchronization of separate devices is presented in Fig. 5. One very important specialty in this solution is that, the satellite connected timing signal directly drives the analog to digital convertors, providing the synchronization at the most precise level. As it is impossible to start all the independent digitizers at the same time, the time gap between the devices is corrected by adding the correct time stamp to each individual data.

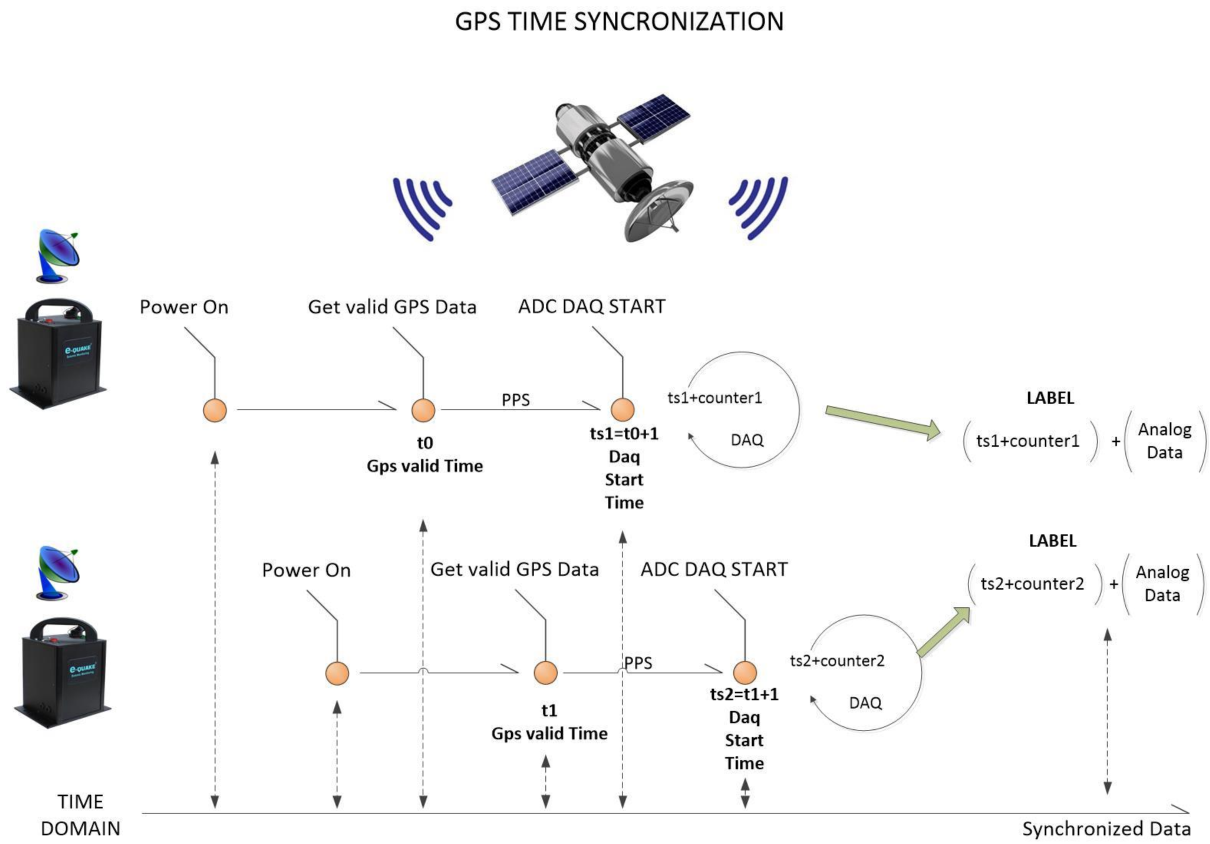

Figure 5. GPS based wireless synchronization method.

Quasi -Static Instrumentation and Monitoring

As well as dynamic monitoring, quasi-static monitoring -primarily based on strain gauges- provide a lot of information regarding the structural health and integrity of the structure. This static instrumentation part is essential for measuring directly the deformations, the position of the neutral axis and sometimes the tilt movement of the structure.

In this study a fiber optic solution is suggested for the quasi-static part. The suggested fiber-optic solution is based on fiber bragg grating(FBG) technology.[10] The main advantages of this technology can be summarized as high multiplexing capability, long-distance transmission, EMI/RFI immunity, electric isolation, signal integrity and long-term stability. This technology especially fits best for the monitoring of long distance spans such as bridges and tunnels.

Another advantage of fiber-optic technology is the wide range of opportunities for the installation of the strain gauges. FBG strain gages are designed to be bonded, spot welded to structures and components (metallic, concrete, etc.) or directly cast into concrete wet mix. These sensors are fiber optic versions of the conventional resistance strain gages but completely passive, offering inherent insensitivity to environmental induced drift. The alternatives are presented in Fig. 6.

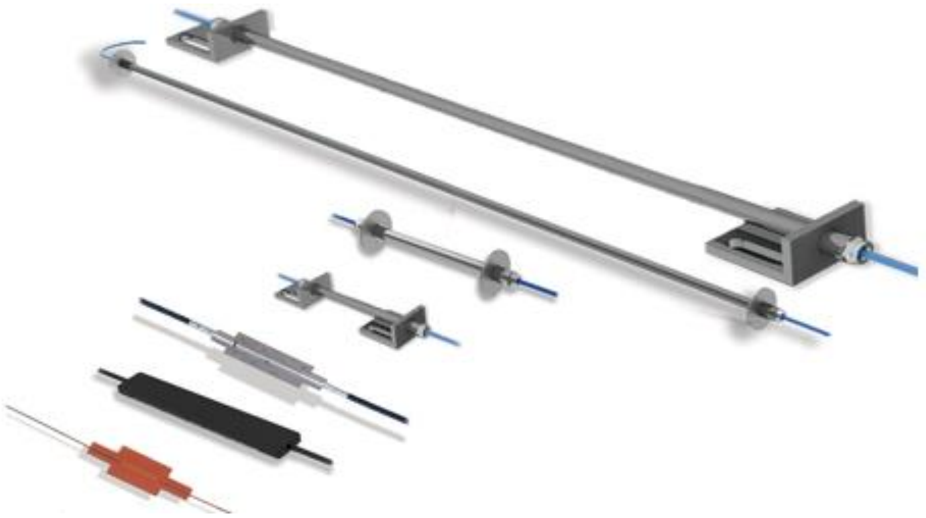

Figure 6. Different versions of Fiber Bragg Grating strain gauges.

A good practice of health monitoring on a steel railway bridge using fiber bragg grating weldable strain gauges is presented by Barbosa et al. [11]

Well-Combined (Dynamic-Static) Integrated Monitoring Approach

A successful and efficient health monitoring instrumentation on bridges can be achieved by a good combination of dynamic and static systems. Especially in long span bridges one of the best and most robust way of static monitoring is using fiber bragg grating based strain gauges and tilt sensors.

On the other hand dynamic measurements should be taken by force-balance, MEMS or MET accelerometers. When the cost performance ratio is considered, MEMS accelerometers are generally the best fitting solution for bridges. However carrying all the analog outputs to a central data acquisition unit is not feasible for long spans. Instead a distributed approach should be followed. The solution of integrated digitizers and accelerometers are considered as the better alternative. In this way it would be possible to distribute the measurements and only transfer the digital data to the central acquisition unit. Certainly the vibration data must be synchronized for modal analysis. GPS based distributed synchronization solves this problem.

The central data acquisition unit should support both fiber bragg grating based static sensors and acceleration based dynamic part. The software should be capable of integrating these two different technologies successfully. Both static and dynamic data should be transferred to remote locations in a well-organized manner. Real-time calculations and analysis should be carried out both separately and sometimes combining the static and dynamic measurements together. Trigger functions in some cases must support the outcomes of both static and dynamic readings.

Monitoring of Tunnels

For tunnels, it is possible to monitor deformation and convergence by fiber optic sensors. A solid case study for this solution was carried out by Barbosa et al. in 2009 for Rossio train tunnel in Lisbon, Portugal[12]. The monitoring system was a complete solution that comprises measurements of strain and temperature with more than 850 fiber Bragg grating sensors, data acquisition, processing, storage and easy access through a web platform. The applied sensing technology has several advantages such as fiber Bragg sensors being immune to electrical interferences and suited to harsh environments. The used method for convergence monitoring (MEMCOT) makes it possible to determine tunnel convergences based on strain measurements around the tunnel contour. An optoelectronic measurement unit and optic switch are deployed at the entrance of the tunnel and remotely connected to a server that saves and displays information to authorized users in web interface. Strain gauge placements and the monitoring system installed at the tunnel, is presented in Fig.7.

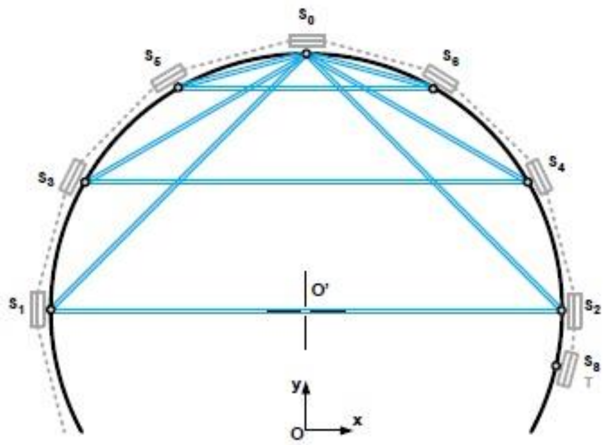

Figure 7. Rossio railway tunnel monitoring by fiber optic strain sensors, strain gauges placed in tunnel cross-sections(right), monitoring system installed at the tunnel(right)

Conclusions

The structural health monitoring instrumentation solutions for bridges and tunnels in parallel with recent technological developments are discussed in detail in this study. For tunnels a completely fiber-optic based solution is possible for to monitor deformation and convergence.

A well-defined combined approach is suggested for the monitoring of bridges. In this approach MEMS or MET based accelerometers are used for dynamic measurements, and fiber optic strain gauges and tilt sensors are used for static measurements. There will be no problem for connection of fiber optic sensors to the central acquisition unit with fiber optic cable. However, for the dynamic part carrying all the analog outputs to a central data acquisition unit is not feasible for long spans. Instead a distributed approach should be followed. The solution of integrated digitizers and accelerometers are considered as the better alternative. In this way it would be possible to distribute the measurements and only transfer the digital data to the central acquisition unit. Certainly the vibration data must be synchronized for modal analysis. GPS based distributed synchronization solves this problem. A 24-bit, GPS enabled digitizer, including a ±2-3 g range MEMS accelerometer which has a noise density figure of 5-10μg/√Hz should be acceptable. Two different data lines are considered along the span of the bridge. One fiber optic line for fiber optic sensors, second ethernet compatible line for the digital data transfer of dynamic acceleration signals. The central data acquisition unit should support both fiber optic static sensors and acceleration based dynamic part. The software should be capable of integrating these two different technologies successfully.

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