High Precision Structural Health Monitoring System using Wireless Sensor Networks

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ABSTRACT: Some advances in extensive bridge monitoring using low cost dynamic characterization Structural Health Monitoring (SHM) systems have excellent potential to improve the regular operation and maintenance of the structures. Wireless Sensor Networks (WSN) have been used to avoid high cost of traditional generic wired systems. The most important limitations in SHM wireless systems are time synchronization accuracy, scalability and reliability.

In this article, a complete wireless system for structural identification under environmental load is presented. Our contribution ranges from the hardware to the graphical front-end. The system is paying attention in avoiding the main limitations of WSN for SHM specially focused in reliability, scalability, and synchronization.

In order to validate the system we have carry out different tests: check synchronization at the lab, compare our operational modal analysis over a real bridge with a numeric analysis and analyze the results of a comparison between couples of signals which belong the same position over the bridge. Obtained results have been excellent and the system has been validated.

1 INTRODUCTION

Use of vibrations as a technique for monitoring structures has been used for a long time. Recent advances in electronics, engineering and data analysis had made possible the use of the structural health monitoring (SHM) analysis as a reliability and accuracy method.

High sensitivity sensors are needed to develop an accuracy dynamic measurement over a structure. The most common used sensors are the accelerometers and depending on the application you need them for, you can choose from a wide range. From the ones with high sensitivity to the ones with wide bandwidth, from the expensive ones to the cheaper, etc.

Using vibrations techniques improves the regular operation and maintenance of structures such as bridges, tunnels, buildings and dams.

In fact, we consider three groups of structures that are very important to measure, some of them continuously. Those are: some of the recently built prominent structures, for example the bridge of Øresund between Denmark and Sweden. On the other hand, older important structures, as the bridge Europabrücke in Tyrol, Austria, that are very difficult to replace. And the third group is the bridges with suspected damage.

For the presented risk groups is important to make a periodic dynamic monitoring campaign to detect the damage as soon as possible. In this way, a proper intervention maintenance campaign can be established.

It is also very important to point out the importance to have a dynamic historical record of a bridge. An isolated measurement over the bridge allows identifying the structural modal parameters of a vibrating structure. But it is only comparable with the theoretical study of parameters of a structural finite element model (FEM).

An objective evaluation of the bridge status can significantly reduce spent money on maintenance, repair, and replacement of the structurally deficient components.

Before an incident occurs, would be more interesting to have the dynamic historical records of the bridge. So after a crash, natural disaster or not planned event against the bridge, a new dynamic measurement of the structure will help us to evaluate the possible damage. The first step for damage detection is modal identification and reconstruction of mode shapes.

The historical records of the bridge are also important to calibrate the parameters of structural FEM with the theoretically undamaged state of the bridge. That calibration is relevant because it is usual for the constructed bridges may be different from theoretically projected ones. If the same FEM model is modified to fit the second monitoring campaign the changed FEM parameters can be used to trace the structural bridge evolution. As much historical records the structure have less uncertainty levels of some variables will influence the modal parameters (Peeters & De Roeck 2001).

The best approximation to the theoretical FEM parameters is to make the first monitoring at the reception stage to get the 'birth DNA' of the structure without any kind of erosion or damage.

During the last decades the most common monitoring systems are compound of a large number of sensors. Each one is wired to a central data acquisition system. That makes the initial cost very high and also very difficult installation and maintenance for the complicated mesh of cables that is implicit in the system.

Mixing the both exposed ideas it is easy to understand that one of the objectives for SHM is to significantly reduce the money spent on maintenance. But the use of expensive wired systems and the cost in time to deploy them makes that the cost for maintenance in civil infrastructures will rise till the estimated \$8.2 trillion in 2010 in United States. According to the study in (Straser et al 1998), up to 25% of the total system cost and 75% of the installation time can be attributed exclusively to the installation of system cables.

For that reason, wireless sensor networks (WSN) are becoming more and more important in this field. In (Lynch 2006), Lynch point out that the combination of smart sensor with wireless communication capability reduce the installation effort and add the capability to extent and help to create a dense array of sensors.

Some of the advantages that WNs offers are that no cables are required for data transfer, which is one of the reasons that reduce the cost of the global system setup and maintenance. Also data processing can be distributed across the network nodes and that makes the system more fault-tolerant.

On the other hand, WNs have also some limitations to be considered. For example time-synchronization accuracy, packet loss, battery life and communication bandwidth are, between others, some of the relevant topics a research have to face.

That is why our goal is the design of a WSN for SHM that solved the problems of reliability, scalability and synchronization. A complete wireless system for structural identification under environmental load is presented in this paper. It had been developed paying special attention on reliability, scalability and synchronization to avoid the main limitations.

To summarize this introduction is essential to understand that the main goals of SHM systems are damage detection, damage localization, damage quantification, and assessment of the remaining lifetime of the structure. For that reason is desirable an economic affordable and easy to deploy system with high accuracy.

The rest of this paper is structured as follows. Section 2 will talk about related work in the SHM field. Section 3 will make a global view of the developed wireless system. Section 4 describes the achievement of a measurement and the experimental results are showed in Section 5. And the end of the paper, in Section 0, the conclusions are given.

2 RELATED WORK

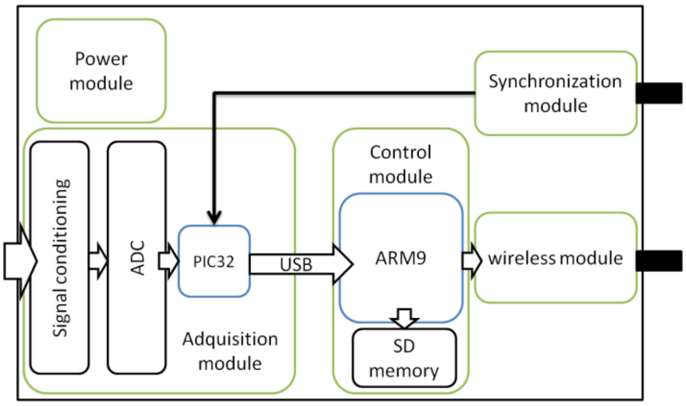
First of all, it is presented the most common tasks and components that are needed for an actual wired monitoring system used for structural identification under operational loads.

Usually a previous finite element model is made to decide the best suitable monitoring locations for the sensors. That task is important because it is normal to have a limited number of available channels in the acquisition system (AC). Placing the sensors in the right positions let the system get better and more structure modes.

Then, over the bridge, the positions of the sensors are marked. The accelerometers are situated and calibrated in their respective positions. The cables are deployed to interconnect each accelerometer with its correspondent channel at the acquisition systems. It is important to take into account that limitations of traffic flow should be restricted to a minimum. The complete measurement is performed, moving the sensor over the bridge to register all the positions that are needed for the reconstructions of the modes. Finally a post processing is carried out to get the identification of the frequencies and modes of the structure. Usually a final report is welcome.

As it was introduced, the WSNs reduce the time and cost to carry the wired test over a bridge. But in the next lines are showed some of the important limitations of the, until now, existing wireless systems dedicated for SHM, especially those relating to synchronization and accuracy in the collected data (Ceriotti et al 2009); (Severino et al 2010).

In the field of SHM, synchronization is a key issue in WNs because a small synchronization error between devices means that is not possible obtains the proper mode shapes. That means that collected data will not be useful for the identification and not comparable with the theoretical calculations. For a correct working minimum synchronization error between two nodes in WNs would be no more than 120 µs. (Bocca et al 2011); (Krishnamurthy et al 2008). Moreover, one of the most widespread methods used to obtain mode shapes of structures is based on frequency-domain decomposition. Using that method a



slight delay in the
Figure 1. Block diagram of the Wireless Node

output response has a strong impact on the mode shapes, particularly for high-order modes (Krishnamurthy et al 2008). Deep studies have been made in this synchronization area showing the effects synchronization-error provokes on SHM applications (Nagayama et al 2007).

Several solutions have been developed for different research groups trying to solve that problem. The first and trivial ideas that come to our minds have to be discarded, some of them for their high error (NTP protocol) and others for their high cost (GPS receivers).

A more spread solutions that were not good enough for our purposes are, between others, RBS (Nagayama et al 2007), FTSP (Maróti et al 2004) or TPSN (Ganeriwal et al 2003). Those systems have a synchronization error between 10 µs and 1 ms, but the most accurate also have an unacceptable accumulative error.

The most used technology to carry out the synchronization in WNs is ZigBee radio protocol for its high performance and low power consumption. On the other hand ZigBee has at least two important limitations. Its small bandwidth that is not adequate for transmission of a great amount of data and its stack layer where some of those layers are not accessible for the developer.

In addition to this lack in synchronization, WNs have to face another big problem, the accuracy in the collected data. Some of the mentioned systems have loss of samples during the data writing process into memory (Bocca et al 2011); (Lynch 2006). Another common limitation in the nodes of a WN is the insufficiency space which marks the limit in the measurement duration (Bocca et al 2011); (Severino et al 2010). It is also significant to point out that any of the WNs used in SHM are 24 bit precision (Aygün & Gungor 2011).

Without those both fundamental features, accuracy in synchronization and accuracy in data collection, the use of WNs are not feasible for SHM.

To solve these limitations a completed wireless measurement system has been developed for SHM. Its maximum synchronization error is far below 120 µs, the number of nodes is not limited, the space for collected data is not limited in the nodes and it uses a very high acquisition modules. That means that with this novel system reliability is no longer an issue.

3 SYSTEM DESCRIPTION

3.1 *General Overview*

The developed system overcomes the drawbacks of existing systems in order to get a complete high precision SHM system with WSNs.

It can be split in two components: server and clients. Server could be a personal computer or a laptop and the clients are the nodes or boxes that contain the accelerometers.

Server is responsible for network configuration, synchronization pulse transmission, measurement parameters transmission and data reception. A laptop or a personal computer with a few additional hardware devices is enough to make the server functions.

Clients are capable of understand the measurement instructions thanks to a special software. Nodes also contain the data acquisition card, the wireless card and the high precision accelerometers for measurement. For the actual prototype is possible to connect from one to four sensors to the same node.

The wireless acquisition nodes and the entire system have been designed with the goal of fulfill the needs of SHM. The system assures the same results of wired systems with the advantages of wireless ones.

The different modules that form the complete wireless system are: power module, manager module, wireless communication module, synchronization module, control module and acquisition module. In **¡Error! No se encuentra el origen de la referencia.**Figure 1 it is showed the different blocks of a node: power, wireless communication, synchronization, control, and acquisition modules. On the other side of the system, the server is compound for manager, wireless communication and synchronization modules.

3.2 *Power Module*

Typical wired systems get the power module from an external power supply which is used to supply the data acquisition system. The sensor’s supply could be transmitted by data or auxiliary wires. On the other hand for wireless systems, each node has its own batteries and the remaining life-time is monitored.

Figure 2. Graphical User Interface

In our case, power module of each wireless node is supplied by lead batteries. Those batteries supply a maximum voltage of 26 V and the system works properly until the supply is fewer than 20 V. One of the functions of this module is to adapt that power to different levels to supply all the modules in the box. A combination of two 12-V lead batteries connected in serial is used, with a 7-Ah capacity and weighing 2.8 kg each. That combination produces a 5.6 kg total and 24-V 7-Ah pack which makes a full working time of each node around 15 h. After that time would be necessary to recharge the battery pack. As is normal, the bigger and heaver these batteries are, the more duration nodes have.

One of the parts of this module is the piezoelectric ICP supply used in structural health measures. That means a module that gives a fixed and controlled 2-mA current to each accelerometer over the same line that sends the data.

Other characteristic of this module is the combination of two switches to control the on-off state of the system. One of them is software controlled and the other is hardware controlled.

3.3 *Manager Module*

It is one of the parts of the server and it is the responsible for the creation of all the connections in the system. Between other operations, manager module establishes the wireless communication between nodes and server; sends parameters and synchronization pulses; receives logs and data files; and generates processed files. To make all these operations a friendly graphical user interface (GUI) has been developed.

The front-end and the background applications that manager module uses, have been developed over Linux, ANSI C, python and Qt languages.

Graphical Interface is available to control three different functionalities: sets the parameters of a measurement setup, controls and setups the reception of data and generates output data following user preferences.

The most complex and important function of this module is the control of setups. When GUI is opened, several TCP/IP sockets are created. A new connection is created when nodes want to establish a stable communication with the server. Server gives a unique and fixed address to each node and throw it is possible to control the setup and monitor the traces sent by the system.

Figure 2 shows an example of the GUI working during a test. It is possible to identify three tabs corresponding to the different functions of the GUI. In the setup tab there is a text space where is possible to read the information that the system and nodes report, and also a column where is showed the connection state of the nodes.

From the reception tab it is possible to choose which channels from each node the user wants to receive. As the data is stored in a SD inside the nodes, it is possible to receive under demand the data even after the test has finished. When a measurement has finished a log file is sent to the server from each node. It is a small file that contains all the information about a measure such as number of samples measured for each channel, size of files, time-stamp of the synchronization pulses, folder where the data is, etc. The reasons for sending the log file instead the full acquired data are dynamism, reliability and scalability.

The communication to send the configuration parameters and to receive the captured data is through a secure shell, SSH, connection to prevent unwanted listeners.

Finally, in the last tab we can manage the received data. The nodes send the captured data in binary files to save space, and here is where it is converted to ASCII files.

3.4 *Wireless Communication Module*

With a wireless system some of the problems of the wired systems are solved such as some cost, time in deployment, etc.

The system presented in these pages uses Wi-Fi, also known as 802.11 protocol, for communication between server and nodes. This protocol does not need a licensed spectrum band because it makes use of an Industrial, Scientific and Medical band. This way data packets and synchronization are clearly differenced. First ones use Wi-Fi and second ones use ZigBee, each one managed with an independent module.

Server has a wireless board capable to create WNs in infrastructure mode. On the other hand each node has its own wireless board to establish the communication with the server over a secure connection.

At this point the server works as an access point (AP) where any device with a Wi-Fi interface has the opportunity to connect. To establish that connection it is needed a WEP or WPA key to assure the security and protection of communications and capture data. With those encryption protocols the communications carried out during measurements is guarantee. With that structure of the network, it is possible to add as many nodes as measurement require, and every node is automatically assigned an IP address. This feature provides a scalable architecture to the system. Once nodes are connected, instructions with different parameters are sent and received through a secure communication using Secure Shell (SSH). That is important to manage the critical data and to grant that the received data has not been corrupted in the transmission. For that reason wireless and remote security issues have been taken into account during the development of the system.

3.5 *Synchronization Module*

As it was commented in the previous section the maximum synchronization error between two separated nodes has to be below 120 µs. If that limit is exceeded the modal results will be affected.

As an independent wireless module from the communication one, the synchronization module is based on the IEEE 802.15.4 protocol standard. There is a master device in the server which sends a synchronization pulse to all slave devices inside the nodes. This technology has a feature which detects energy in the 2.4-Ghz band and acts upon detection. As it was commented previously one of the problems of this protocol is the stack layer overhead. Call functions from physical layer to application layer can randomly delay the pulse detection making the synchronization process unstable. For that reason lower layers have been implemented to make a direct call from physical layer to application layer, avoiding all the intermediate stack layers.

Slave module generates an interruption at the exact moment that the energy is detected in its operation band. That interruption is rapidly attended in the PIC32 microcontroller internally assembled in each node. The time reference number of sample couples are stored in that moment with a 32-bit resolution timer reference. Those 32-bit timers allow the system to detect differences in the signal under 10^{-9} seconds. As the energy pulse cross directly from the physical layer to the application layers, is much faster and not require any additional processing.

Server can transmit synchronization pulses to the nodes at any time in order to set sync marks that will be used in the post process. All those additional timestamps help to correct small deviations between internal oscillator-based hardware clocks in a long measurement series.

With statically positioned nodes, structures of hundreds of meters can be measured. But if a sync pulse is sent before placing nodes over the bridge the structure could be thousands of meters. That is possible because more sync marks can be requested during the measurement process. After that a simple post processing algorithm with decimation and interpolation operations increase the accuracy.

The activation of all ADCs in nodes is also synchronized with an energy pulse. That reduces to minimum the clock error between nodes. The numbers obtained in laboratory test show that the difference between pulses received in separated nodes is about 80 ns. To correct the small deviations in the signals due to the frequency clock of the nodes which have an error of 25 ppm, the continuous sync pulses are used.

These couples' sample timer number are sent in a log file to the server were they are analyzed. As the sync marks are sent from the server, an exact time between marks is known. It is also known that two data files of different nodes should have the same number of samples between time-marks. Post processing in the server can be applied if a little jitter is detected.

To sum, the synchronization module provides a great time reference with less than 125 ns difference between nodes. The extra sync pulses received are used to fix derivations in the frequency clocks. That combination provides a reliable test.

3.6 *Control Module*

From this module the rest of modules are managed. It is based on an ARM9 microcontroller running a Linux kernel 2.6 operating system. The main board contains the microcontroller and also the communication interfaces and external storage on an SD card. A 2-Gb SD card is attached to each node to store measurements. With that is possible to store a 500 min of data. External storage solves the reliability problems of wireless systems because operators control when the captured data is deleted and it can be extracted at any time. Other communication interfaces integrated in the main board are: two USB ports and serial interface for debugging. A wireless USB adapter is connected to the board. And the other USB port is used to receive the data from the PIC32 microcontroller.

3.7 *Acquisition Module*

This is a critical component of all current measurement systems. Piezoelectric accelerometers are the most widely spread sensors in the SHM area when a high resolution if required. Some of those accelerometers could reach the resolution of 0.000001 g, which implies that their signal should be acquired with high-resolution analog-to-digital converters (ADCs).

Wireless nodes are equipped with two low-noise ADCs with a sample rate between 1 and 192 kHz and a 24-bit resolution. Each ADC is formed with two differential inputs that provide up to four channels in each node. Also, additional characteristics are embedded in the ADC such as linear-phase, digital control of the sample rate, high-pass filters, antialiasing filters, etc.

An additional circuit adapts the signal generated from the ICP accelerometers, filters the noise and supplies the power needed for the ADCs.

The frequency used to sample data for our purposes is 3906.25 Hz. That frequency is more widely that the system needs for SHM applications. The reason of that oversampling allows making some post processed operations as digital filtering. For identification modes in bridges the typical frequencies are over 1-100Hz.

Finally the digitalized information goes through the USB interface, as a serial gateway of communication between PIC32 and ARM9.

4 HIGH PRECISION MEASUREMENTS

In this section a measurement process is followed to understand the importance of high precision in this kind of systems.

One of the advantages of the design of this wireless system is the possibility to measure multiple structures on the same day. In most cases the estimated time to place accelerometers, make the measurement, the identification and pick up back the equipment would be around 2 hours.

Traffic cannot be closed off for a great number of structures during the test using this movable dynamic monitoring system for structural identification under operational (environmental) loads. That is another advantage of wireless systems and individual nodes over a wired system.

The novel wireless system uses high resolution sensors with the characteristics showed in Table 1.

Table 1. Characteristics of a high resolution accelerometer

Performance	Value
Sensitivity	10.0 V/g
Measurement Range	0.5g pk
Frequency Range	0.1 to 200 Hz
Broadband Resolution	0.000001g rms

The sensitivity is the relation between the accelerations (g) register by the sensor and the output signal (volts) that are given for them. For ICP sensors the output signal is bounded between ±5V.

Measurement range is the upper and lower limits of what the accelerometer can measure. A smaller measurement range means a more sensitive output; it is possible to get a more precise reading out of an accelerometer with a low measurement range.

That means that the maximum absolute values of acceleration that can be registered in our system are ±0.5g, giving an output signal of ±5V.

The frequency range is the range where the accelerometer works in a proper way with a stable behavior.

And the broadband resolution is the smallest acceleration value that is distinguishable for the sensor.

Interpreting in the right way those values we are able to calculate the minimum bits needed to store

$$10(V/g)x0{,}000001(g) = 0.00001(V) = 10(\mu V)$$

the captured data without losing resolution in any of the measurement steps.

$$\log_2\left(\frac{10}{10^{-5}}\right) = 19.93 bits$$

To get the resolution of the sensor in volts it is needed to multiply the sensitivity by the broadband resolution as follows:

To get a lower step than 10 µV are needed:

And that is the reason why a minimum of 20 bits are needed to capture and store the accelerations without losing resolution.

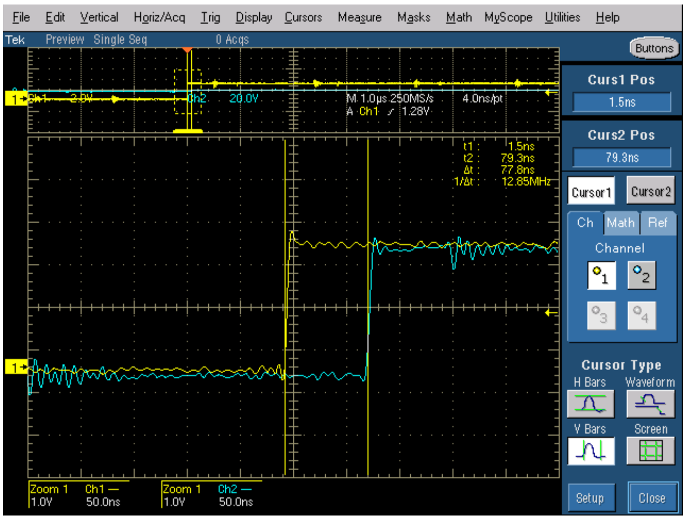
Each of the developed nodes contain four 24-bit resolution ADC to support even better accelerometers if is needed.

To start a measurement, after all the nodes are placed in the right positions over the structure, the parameters should be sent from the server to the nodes. By choosing number of samples to measure or duration of the measure, the other parameter is automatically obtained because the sample frequency is set to 3906.25 Hz. If the nodes are properly connected, submitting the parameters in the GUI, the instructions are broadcast by Wi-Fi to each node. A feedback of the communication state is showed in the GUI.

When the instruction is received for the nodes enter in a waiting state pending the synchronization pulse to start the measure. The measurement process has priority over any other process in the system to guarantee no loss of samples in the measurement process.

An initial sync pulse should be sent from the GUI to initialize the measurement. Then the energy pulse is broadband over the 802.15.4 radio protocol starting the collection of data in the nodes with the parameters previously establishes.

We want to highlight again that two different protocols are used: Wi-Fi for communication instructions and transmission/reception of data and IEEE



802.15.4 for synchronization.

Figure 3. Synchronization error detail between two different nodes.

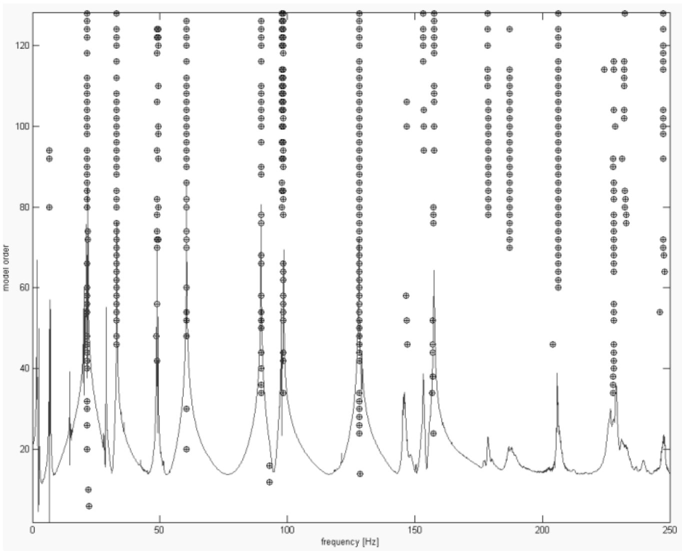


Figure 4. Stabilization Diagram obtained via MACEC software

A progress bar in the GUI shows the remaining time to finish and in which moments the time-marks are sent so the operator has a visual evolution of the measurement.

During the measurement and collecting data process each node stores the four-binary parallel channel data on an SD memory card. Then when that process has finished a log file is sent to the server with a summary of the captured data: name of the stored files, path, size and couples time-marks sample.

Data stored from this or previous measurements that are stored on the SD card can be retrieved now. Also, a new measurement can be started from the server.

The speed of the wireless communication over SSH connection may vary, but on average, is at a rate of 1.3 MB/s.

Once the binary files are received for the server, it is possible to decode or work with them at the same time that other measurement is performed. That is because while the nodes are busy capturing data, the server is free of process.

With the decoded high precision captured data it is possible to obtain the stabilization diagram of the structure. That diagram is a key tool in modal analysis (Heylen et al1997) and a method for automated interpretation of stabilization diagrams is used (Reynders et al 2011). It has been observed that in many modal identification problems the physical modes of the structure show up as vertical lines in that diagram, while other, for example the spurious modes, do not. Using the MACEC software for modal testing the frequencies and modes of a structure as a bridge are obtained and the results are valid to calibrate the theoretical FEM models.

5 EXPERIMENTAL RESULTS

In the previous sections a novel wireless system for Structural Health Monitoring has been presented and four groups of experimental test have been carried out to validate it.

Laboratory tests are achieved to check the synchronization module. After that a laboratory beam is measured and the full system is evaluated. The third step is to carry out an operational modal analysis (OMA) on a real structure. Finally, the signals corresponding to two different accelerometers, placed on the structure at the same time and position but in different nodes, are compared.

5.1 *Laboratory Tests. Synchronization.*

To achieve a high precision measurement in wireless systems synchronization is a key issue in the system. The two synchronization problems that researches have to face are temporal jitter and spatial jitter.

The first one is generated for clock deviations caused by event handling, uneven clock ticks, or other hardware biases. To solve that problem a specific processor without operating system is used. A test program haven been run over several months to confirm a stable data rate and to see the very low crystal oscillator deviations are under 25 ppm.

The time-synchronization errors between different wireless nodes are known as spatial jitter. These differences between different nodes have significant effects on the identified mode shapes. It is easy to see how important is to reduce this error to minimum thinking in a row of three nodes, where when the center node is going up, the other two should go down to see one of the modes.

Figure 3 shows a screenshot taken with the oscilloscope where two nodes are connected to two different channels. Red and blue signals show when the interruptions in the closest and furthest nodes are generated. An average spatial jitter of 80 ns and a typical deviation of 10 ns have been measured. In the worst case the obtained time separation was 125 ns.

5.2 *Laboratory Test. Beam OMA.*

A laboratory IPE330 beam, 4 meters long and 200 kg weigh has been measure with 4 sensors and 16 measurement points.

The sensors are placed in four different positions making a global test of four setups. Capturing data during 1 min in each setup, and using MACEC, the stabilization diagram showed in Figure 4 is obtained. These results are compared with the theoretical FEM analysis showing the high quality of the captured data.

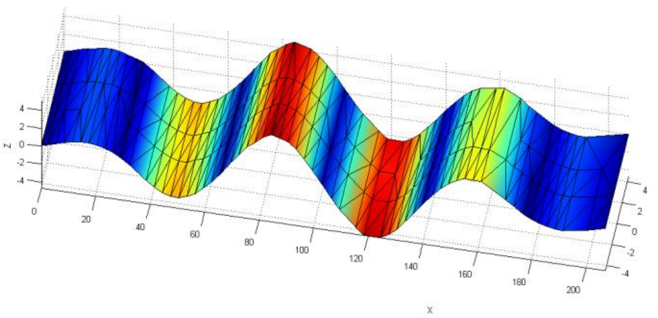


Figure 5.Modal shape of a bridge

5.3 *Real Test. Bridge OMA.*

A real bridge for high speed trains is measure to make a complete validation of the wireless system. Figure 5 shows the 207 meters bridge, compound of 6 vain and box section situated in the north of Spain.

The carry out test establish 300 measurement points using 28 accelerometers, where 8 of them are reference ones and have fixed positions and the other 20 are movable.

For the measure15 setups of 10 min are needed using 7 nodes with 4 channels each.

The obtained operational modal results are compared against a FEM of the structure and a commercial wired system. The FEM modal parameters are very accurate and the comparison with the wireless system can certify the proper functioning of it.

The measurements have been carried out with the bridge completely finished but before installing the train rails. That means the only excitation of the bridge is wind.

Due to the difficulty of calibrating a FEM with the existing structure and by not considering some small elements such as the side barriers, some differences are found between the identified frequencies and the theoretical ones.

5.4 *Wavelet-Based Semblance Analysis*

An additional test has been put into practice to contribute with more information of the complete wireless system developed to the characterization.

In figure 9 there are some of the results of a wavelet-based semblance analysis applied to couples of signals placed in the same position but connected to different nodes. It can be seen the time series superposition between roving and reference sensor for each couple of signals.

The colored map returns the semblance value for a set time instant at a certain frequency value. Red color indicates a perfect phase correlation and blue color indicates the contrary, a phase shift equal to ±π.

6 CONCLUSIONS

This work makes three main contributions to SHM systems. The first one is to fulfill the requirements needed to obtain high quality data to be used for current and future operational modal analysis. With this purpose, a wireless acquisition system with high-frequency sampling together with a very reliable time synchronization accuracy and low jitter, not provided by previous works, has been developed. Spatial jitter has been reduced to 125 ns, far below the 120 µs required for high-precision acquisition systems. The second contribution is a system designed with the ability to scale to a large number of nodes. This way, a dense sensor coverage grid of real world structures becomes possible. Finally, this network has been tested in a real world structure solving a myriad of problems encountered in a real deployment in difficult conditions.

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