Some advances in extensive bridge monitoring using low cost dynamic characterization

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ABSTRACT: Dynamic measurements will become a standard for bridge monitoring in the near future. This fact will produce an important cost reduction for maintenance. US Administration has a long term intensive research program in order to diminish the estimated current maintenance cost of US$7 billion per year over 20 years. An optimal intervention maintenance program demands a historical dynamical record, as well as an updated mathematical model of the structure to be monitored. In case that a model of the structure is not actually available it is possible to produce it, however this possibility does not exist for missing measurement records from the past. Current acquisition systems to monitor structures can be made more efficient by introducing the following improvements, under development in the Spanish research Project "Low cost bridge health monitoring by ambient vibration tests using wireless sensors": (a) a complete wireless system to acquire sensor data, (b) a wireless system that permits the localization and the hardware identification of the whole sensor system. The applied localization system has been object of a recent patent, and (c) automatization of the modal identification process, aimed to diminish human intervention.

This system is assembled with cheap components and allows the simultaneous use of a large number of sensors at a low placement cost. The engineer's intervention is limited to the selection of sensor positions, probably based on a preliminary FE analysis. In case of multiple setups, also the position of a number of fixed reference sensors has to be decided. The wireless localization system will obtain the exact coordinates of all these sensors positions. When the selection of optimal positions is difficult, for example because of the lack of a proper FE model, this can be compensated by using a higher number of measuring (also reference) points.

The described low cost acquisition system allows the responsible bridge administration to obtain historical dynamic identification records at reasonable costs that will be used in future maintenance programs. Therefore, due to the importance of the baseline monitoring record of a new bridge, a monitoring test just after its construction should be highly recommended, if not compulsory.

[1] The authors acknowledge financial support from the Spanish Ministry of Science and Innovation (project reference P8/08) within the National Plan for Scientific Research, Development and Technological Innovation 2008-2011

1 INTRODUCTION

Monitoring of structures using vibrations techniques has been used for a long time, for example, by experienced workers that listened to the sound transmission through the railroad rails. This dynamic measurement technique applied to bridges requires the use of high sensitivity sensors. Among them, accelerometers are the most common ones but strain gauges, displacement or velocity transducers etc. are also used.

In civil engineering, monitoring of public works with a high human safety risk is standard. This is for instance the case of dams. Actually, some of the recently built prominent structures are continuously measured. The data are sent to a control centre where it is automatically processed. In this way any incident can be easily known, evaluated and if necessary, correction measures can be applied. The bridge of Øresund between Denmark and Sweden is probably one of the best examples, as explained in Peeters et al (2009). It has 7845 m total length and is supported on a big number of piles. The central pylons with a height of 204 m are designed to resist an aeroplane crash. Although the ship free height is 57 m, most shipping traffic prefers to pass through the unobstructed Drogden Strait. There is combined traffic of automobiles and trains with 20 min frequency. All of these characteristics make the safety and the cost of maintenance an important task. This kind of bridges is not considered in this paper, because the control process is built ad-hoc in a very complex way. Nevertheless they illustrate the importance of continuous monitoring in structures where safety is a big issue.

On the other hand, older important bridges as the Europabrücke in Tyrol, Austria are very difficult to replace. The traffic growth plus the structural deterioration have made the use of continuous monitoring necessary in order to know the possible structural damage, as well as to estimate the structural remaining life.

A third group are the bridges with suspected damage that are dynamically monitored and a periodic report as shown in Wenzel (2009) is obtained. In this way, the structural parameter evolution can be known, but the cost of continuous monitoring is high.

There is a large number of only visually inspected bridges, for which important damage is not discovered, i.e. several broken internal prestress cables, or they are difficult to inspect, as box girders without inspection pipe. In these bridges a periodically programmed dynamic monitoring campaign may lead to an early detection of damage. In this way, a proper intervention maintenance campaign can be established. Moreover, if a sudden accident happens that could compromise the structural safety, as an underneath track crash, the dynamic historical records are quite important to evaluate the possible damage. An isolated campaign allows identifying the structural modal parameters (eigenmodes and natural frequencies) of a vibrating structure but makes it nearly impossible to assess damage in a not clearly affected structure. On the other hand, historical records allow calibrating the parameters of a structural finite element model (FEM) with the theoretically undamaged state of the bridge. 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. More records will allow improving the system and reducing the uncertainty levels of some variables (e.g. the temperature) that influence the modal parameters, as it is shown in Peeters et al (2001).

Historical records are very important in order to apply this approach. A very convenient time for the first monitoring is at the reception stage. This dynamic test could be added to the standard official static load test already implemented in many countries.

According to USA National Bridge Inventory (NBI) (1995) of the Federal Highway Administration (FHWA), there are 10 levels to rate the actual state of a bridge. They go from, "failed condition" (0), to "excellent condition" (9). These are based on visual inspection and are a large scale to be easily applied. A shorter scale to measure the structural risk level from 0 to 5 combining the visual inspection and dynamic measures, as used in BRIMOS® software, would be more useful. This software combines this two plus a FEM updating based on experience in more than 1000 study cases as mentioned in Wenzel (2009). Using a scale of (A) good condition, (B) good condition with local damage, and (C) problematic conditions, applied to visual inspection, dynamic measure and FEM, give a risk level from (1) low level, to (5) extreme. As a result, the BRIMOS program gives some recommendations and actions associated to these levels. The NBI limitations to include the dynamic test rating on bridges has led the FHWA to de-

velop the Long-Term Bridge Performance program (LTBP), where some bridges has been chosen to work out structural health monitoring (SHM) techniques. New world standards are expected within the lifetime of this project started on 2007.
The goal of SHM systems is to assess the level of damage. This can be done to different extents according to the following order:
- Dynamic monitoring test records.
- System identification. It will allow to get the modal parameters (natural frequencies, eigenmodes and damping coefficients)
- Damage detection. Comparison to previous measurements can lead to a suspicion of damage.
- Damage location. A further study can help to get the location of damage.
- Damage evaluation, e.g. by applying FEM updating. Damage extent. The importance of damage must be assessed.
- Remaining life time. A clear understanding of these axioms given in Farrar et al (2005) is necessary to carry out this process.

Section 2 will describe the current removable systems for applying structural identification as well as their requirements and limitations to be used as a standard procedure. The Spanish Project "Low cost bridge health monitoring by ambient vibration tests using wireless sensors" aims to develop a quick monitoring and identification system to be applied to a large number of structures at a reduced cost. The features of the newly developed system are explained in Section 3. Section 4 details the wireless system developed within this project by the Technical University of Madrid (UPM). Section 5 summarizes the improvements introduced at the K.U.Leuven in order to simplify and automate the data analysis. Conclusions and further research are described in section 6.

2 ACTUAL MOVABLE SYSTEMS

In this section, the most common tasks and components of the actual movable dynamic monitoring systems used for structural identification under operational (environmental) loads are described. The description is limited to accelerometers as they are the most commonly used sensors. It has been taken into account that a great number of candidate bridges to be monitored would not allow a complete closure of traffic during the tests. Limitations of traffic flow should be restricted to a minimum.
- Make a finite element model or structural model to decide upon the best suitable monitoring locations for the sensors. Optimal placement allows getting a large number of modes with a minimum number of accelerometers. The number of possible sensors can be limited by the number of channels available in the acquisition system (AC).
- Mark the previous locations on site over the bridge deck. Distances from reference points are required.
- Place sensors on a stiff plate with a levelling system and level them.
- Keep a record of the measurement points and the placed sensors. This information is required to apply the calibration parameters of the sensors when processing the data.
- Get a close location for the acquisition system. It must be weather protected, connected to a computer and to an electrical power generator. These limitations plus the traffic flow safety make it usually difficult to get a proper placement close to the bridge.
- Connect every sensor by cables to the acquisition system. Long length cables might be needed. Bad connections or long cables introduce noise in the measurements. Some cable layout underneath the bridge could be required to avoid traffic influences.
- Keep record of what is connected on both sides of a cable, that is, position or sensor in one side and number of channel in the AC. Clearly labelled cables, sensors and channels are required, and a double check is compulsory to avoid problems. Configure the system, and start a test phase to assure the right connections of every channel.
- Perform the test. The complete measurement could require having several setups. In each setup all the sensors get data at the same time at given locations. In all the setups some common sensors (reference sensors) are required and others (roving sensors) can be moved to other locations. The identification software must be able to deal with multiple setups, but

it has the advantage that less sensors or AC channels are required. Total cable lengths can be dramatically reduced, especially if a large number of measuring points are needed to get the modal parameters. On the other hand, it introduces extra time needed for measuring each setup including also the time for moving the roving sensors

- Post processing of the data to get the eigenmodes and frequencies. MACEC (Reynders et al, 2011a), ARTEMIS and LMS Test.Lab are examples of software capable to make this analysis. The following data are required:
    - Sensor time data.
    - Calibration parameters of the sensors: conversion of the electrical signal (volts or intensity) into accelerations. This can already be introduced in the AC system or in the post processing.
    - Correlation between the acquisition channel number and the sensor to correctly apply the calibration parameters.
    - Correlation between the channel number and the geometrical coordinates of the sensor are needed to plot afterwards the eigenmodes.
- Write a report.

3 NEWLY DEVELOPED WIRELESS SYSTEM

This project deals with overcoming the drawbacks of existing systems in order to get a complete low cost system for structural identification. Main goal is to get the dynamic parameters in a few hours' time. Comparison of these parameters with future measures will allow to track damage and to proceed with further investigation of the state of the structure.

The actions undertaken to surpass existing systems are summarized as follows:

- Build a wireless acquisition box with a high sensitivity sensor inside.
- Wireless data communication to retrieve data from the box to a computer.
- The wireless system should allow synchronization among boxes in less than 125 ns.
- Automatic wireless localization system to get the relative position of each sensor (data acquisition box) on the bridge
- Adaptation of the MACEC software to get automatic dynamic parameter extraction (natural frequencies, eigenmodes and damping coefficients) and production of a short summary report without the need of human intervention.

The working procedure can be summarized in the following steps:

- Compare the structural type with some standard ones defined in the system and input this data with the name, the location and a picture of the bridge into the computer.
- Decide the position of the reference points over the bridge to place there some of the location boxes (Section 4.7). ,e.g., the joints and the bridge abutments.
- Distribute wireless acquisition boxes taking into account the structural type and the existing traffic.
- Send a pulse through the Zigbee usb controller card to start the synchronization.
- Activate the localization system to automatically get the coordinates of the acquisition boxes.
- Retrieve the following data from the acquisition boxes:
    - Identification of the box and the present versions of hardware and software.
    - Identification of the sensors connected to each numbered channel and the associated calibration parameters.
    - Data series of each channel.
- Retrieve the following data from the localization boxes:
    - Identification of the box and the present versions of hardware and software.
    - For each localized box, the coordinates relative to the localization box.
    - The number of the localized box using automatic video identification software.
- Store the recorded measurements. Run the automated structural identification version of MACEC to get the modal parameters and the summary report.
- Store the identification results with the log file generated with it. This will help to understand the parameters used in the automatic software version and any useful data concerning this analysis.

It is expected that the previous steps for a 3 span bridge with a total length of 100 m can be done in little more than 2 hours. This makes this system very appealing to be applied to a set of selected bridges without historical dynamic records where visual inspection is not enough to fulfil the actual maintenance requirements. The proposed method does not need a prior FEM model. This is actually one of the more time consuming tasks in SHM techniques, because this model has to be carefully constructed. In most cases the structural numerical model of the bridge or detailed plans of the structure are not available. Even in the case that all this information is available, the FEM model will be different from the real structure. Extra work will be required to calibrate the FEM model with the measurements. Constructing and calibrating a FEM model is very expensive to apply as a routine maintenance campaign as changes are not expected for a large amount of bridges. Only when damage is observed a FEM model is needed and further studies must be carried out.

Ad hoc FEM models and subsequent updates to fit the maintenance campaigns must be carefully stored in case they are available. Certainly in the case of newly built bridges this is highly recommendable.

A very important improvement of this system comes from the patented localization system. It avoids drawing over the deck of the bridge the predefined sensor locations obtained from a FEM model. By automatically positioning the boxes (the sensors) and by automating the data retrieval and the subsequent system identification, a structural identification in situ becomes possible.

4 DESCRIPTION OF WIRELESS ACQUISITION SYSTEM

Our system is based on two components: a host personal computer that it is called server and boxes or nodes called clients. Server has the necessary hardware and software for network configuration, measurement parameters transmission, synchronization pulses transmission and data reception. In our application server is a laptop, but it is possible use a personal computer.

Clients have the software necessary for understanding the measurement instructions, a data acquisition card and appropriate sensors (between one and four per box) for measurement.

The wireless acquisition boxes and the entire system are designed with the goal of SHM. System assures the same results of wired systems with the advantages of wireless ones.

In this section, different system modules are described briefly (Fig. 1). The system could be divided into power module, acquisition module, wireless communication module, synchronization module, control module, manager module, and location module. Clients present power, acquisition, wireless communication, control, synchronization modules, and, in some cases location modules (location boxes) and server is composed of wireless communication, synchronization and manager modules.

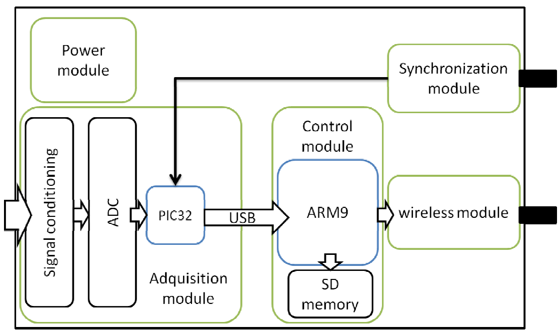

Figure 1: Block diagram of wireless bridge health monitoring boxes.

4.1 Power Module

In wired systems the sensor supply could be transmitted by data or auxiliary wires. Wireless systems must use batteries and battery life must be monitored. Each wireless box has their own power module supplied by lead batteries. The batteries supply a voltage of between 20 and 26 volts over their life span and a maximum peak current of 3 amperes. This voltage is converted to different levels in order to supply to all the modules in the box.

Finally, each box has a soft switch off and switch on implemented in two different ways: remotely, thanks to the wireless module or with an external switch installed on the boxes.

4.2 Acquisition Module

Acquisition module is a critical component of all current measurement systems. In the area of SHM, piezoelectric sensors are the most commonly used sensors for high precision. Better families of sensors could reach a resolution of 0.000001 g which implies their signal should be acquired with high resolution analog to digital converters.

Wireless box is equipped with two low-noise ADCs with a sample rate between 1 KHz and 192 KHz and a 24-bit resolution. The signal conditioning circuit adapts common signals from ICP sensors to differential, filters the noise and supplies the necessary current for the ADCs.

The digitalized information is through a USB interface, thanks to a PIC32 microchip which creates a SPI-USB gateway, to the control module.

4.3 Synchronization module

For a correct working minimum synchronization error between two boxes would be no more than 120 µs (Sazonov, 2010). If this limit is exceeded the modal results could be affected.

To get this requirement we propose a wireless synchronization module with IEEE 802.15.4 technology. Boxes have an integrated CC2530 module for receiving periodic pulses transmitted by another CC2530 which is the coordinator. Synchronization pulses can be transmitted to the boxes at any time in order to set sync marks that will be used in the post-process. These correct the small deviations between internal oscillator-based hardware clocks. This way, system offers full flexibility to create synchronization marks at any moment or in any setup.

Finally, when the measurement has finished, the boxes send the couples' sample timer-number to the server where they are analyzed.

To summarize, the sync module provides a great initial reference to the system, with less than 125 ns difference between all boxes. The next pulses that arrive to the boxes are used to fix deviations in the frequency clock. Using this approach we obtain good first initial pulse synchronization, correct internal deviation and provide a reliability test.

4.4 Wireless communication module

As explained in the introduction, the wired systems have some inconveniences that wireless systems try to resolve, like the cost of the wires, the deployment of the system on the bridge, etc.

The system presented in this paper uses the 802.11 protocol, also known as Wi-Fi, for communications between the boxes on the structure and the server that runs on a laptop. This protocol uses an ISM band, which does not need a licensed spectrum band. This way all communication packets are sent via Wi-Fi using its large bandwidth, and Zigbee radio interface is dedicated only to synchronization. The wireless box has a wireless interface connected to the main board equipped with drivers to control and configure the device. In the same way, the laptop has a wireless interface which has the ability to create wireless networks in infrastructure mode.

4.5 Control module

Control module is responsible for managing all previous modules. It is based on an ARM9 microcontroller. This microcontroller is integrated into the main board which provides communication interfaces and external storage on an SD card where the measurements are stored temporarily.

4.6 Manager module

Manager module is included in the server device. It creates all the connections in the system, for example, between boxes and server, it sends instructions and synchronization pulses, and it receives the measurements and generates the processed files. A friendly graphical user interface, GUI, to manage different resources has been developed. This GUI has three different functionalities: setup control, reception of data and generation of output files.

4.7 Location module

Location module can be included in one or more client device. According to the sensed area two or more location device are needed. Its main function is to provide global localization of each sensor. Localization module is equipped with a webcam and a servomotor connected to control module. This module provides a full image scan on the sensed area detecting different specific color stickers over each box as shown in Fig. 2.

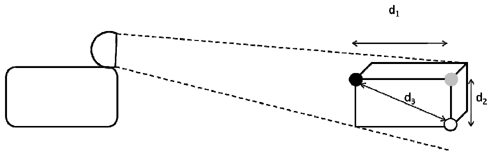

Figure 2: Location module operation.

All these images are sent to the server and a processing image algorithm is executed to extract an absolute position based on location devices. These devices have to be located using absolute references.

5 AUTOMATED MODAL PARAMETER ESTIMATION

The current practice in output-only modal parameter estimation involves a high amount of user interaction. So far, this has to a large extent prevented the spread of modal testing to structural health monitoring applications. One of the goals of this project has been to reduce user interaction as much as possible without compromising the accuracy of the modal parameters estimates. So far, the efforts have concentrated on the most time-consuming step: the selection of a set of physical modes from a stabilization diagram.

All parametric modal identification algorithms require at least one user-defined integer: the system order n, which ideally equals twice the number of natural frequencies. As this number is unknown in practice, and as the assumptions on which the identification is based are only approximately met, the standard approach is to perform the identification for a wide range of model orders, and to plot all modes in an eigenfrequency vs. model order diagram, called *stabilization diagram*. In a very large number of modal identification problems, it has been observed that the physical modes of the structure show up as vertical lines in this diagram, while the other, spurious modes, do not. Although this diagram has become a key tool in modal testing (Heylen, 1997), the selection of physical modes as columns in the diagram is often not straightforward, the results may depend on the judgment of the analyst, and possible additional validation criteria may be needed.

In the framework of this project, a method for automated interpretation of stabilization diagrams has been developed (Reynders et al., 2011b), that fulfills the following 5 target criteria:
1. not rely on more than one data record or on prior estimates;
2. be as physically intuitive as possible and follow the course of a manual analysis;
3. produce similar results as in a manual analysis;
4. be of use in an EMA, OMA, and OMAX approach;
5. not contain parameters that need to be specified or tuned by the user.

The method is unique in the sense that all alternative automated modal parameter estimation methods known to the authors breach at least one of these targets; in particular, the all need user-specified parameters or threshold values. The method involves clustering in 3 stages:
1. All modes in the stabilization diagram are classified into two categories: probably physical and certainly spurious. A partitioning method is employed, that makes use of as many relevant single-mode validation criteria as possible. The modes that are classified as spurious are removed from the diagram. This first stage automates the setting of the stabilization thresholds, performed by the user to obtain a clear diagram.
2. Similar modes in the cleared stabilization diagram are grouped together. Hereto, hierarchical clustering is employed, where the cut-off distance is not a user-defined quantity, but based on

the results of stage 1. This stage corresponds to the visual inspection of the stabilization diagram by the user, in order to detect vertical lines of stable modes.
3. The clusters are grouped into two categories, physical and spurious modes, and a single representative mode is chose from each physical cluster. The number of modes in a cluster is used as a validation criterion. This stage corresponds to the selection by the user of a representative mode from columns of stable modes in the diagram.

A validation study has been performed, where nine benchmark operational modal bridge data sets were analyzed, and the resulting modal parameters were compared with those obtained by an experienced analyst. With the automated approach, all relevant modal parameters were recovered with similar accuracy as in the manual analysis (Reynders et al, 20011b). The method is to be implemented in the MACEC software for modal testing (Reynders et al, 2011a).

6 CONCLUSIONS

A complete system has been developed that makes it possible to have low cost vibration monitoring and structural parameter identification of a common bridge in a very short time. In most cases the estimated time to place sensors, do the measurement, the identification and remove the equipment would be around 2 hours. Therefore, a large amount of bridges, which can be considered as potential candidates to be monitored, can actually be investigated as part of a maintenance campaign.

Moreover, the importance of historical records should be emphasized. New bridges must be dynamically measured to get a signature of the original structure. Probably a standard procedure has to be defined. The cost of this system is remarkably low compared to the construction cost. For medium importance existing bridges a special campaign to get this first record would became quite interesting even if no other subsequent measures are actually planned. In the case of future suspected damage, or accident, the historical record will be highly valued to provide a measurable extent of damage.

REFERENCES

- Bjerrum, J., Larsen, E., Bak, H., and Jensen, F. Internet-based management of major bridges and tunnels using danpro+. In Conference on Operation, Maintenance and Rehabilitation of Large Infrastructure projects, Bridges and Tunnels, Copenhagen, 2006.

- Farrar, C., Worden, K., Mansin, G. and Park, G. Fundamental Axioms of Structural Health Monitoring. Proceedings of 5th International Workshop on Structural Health Monitoring. 2005. Stanford, CA. U.S.

- Heylen W., Lammens S., and Sas P. *Modal analysis theory and testing*. Department of Mechanical Engineering, Katholieke Universiteit Leuven, Leuven, Belgium, 1997.

- Peeters B., Couvreur G., Razinkov O., Kuendig C., Van der Auweraer H., and DeRoeck G. Continuous monitoring of the Oresund Bridge: system and data analysis. *Structure and Infrastructure Engineering*, 5(5):395-405, 2009.

- Peeters B. and De Roeck G. One-year monitoring of the Z24-bridge: environmental effects versus damage events. *Earthquake Engineering and Structural Dynamics*, 30:149-171, 2001.Wenzel, H. Health Monitoring of Bridges. John Wiley & Sons. Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, 2009.

- Reynders, E., Schevenels, M., and De Roeck, G. MACEC 3.2: A Matlab toolbox for experimental and operational modal analysis. Technical Report bwm-2011-01, Department of Civil Engineering, K.U.Leuven, February 2011.

- Reynders E., Houbrechts J., and De Roeck G.. Automated interpretation of stabilization diagrams. In T.Proulx, editor, *Modal analysis topics, Volume 3*, Proceedings of the 29th International Modal Analysis Conference Series, pages 189-201, Jacksonville, FL, February 2011. Springer.

- Sazonov E., Krishnamurthy V., Shilling R. “Wireless intelligent sensor and actuator network. A scalable platform for Time-synchronous applications of structural health monitoring”. Structural Health Monitoring.vol 9:465-476. September 2010

- Wenzel, H. and Pichler, Dieter. Ambient Vibration Monitoring. John Wiley & Sons. Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, 2005.