

Wireless Acoustic Emission Sensor Networks for Structural Health Monitoring in Civil Engineering

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Abstract. The inspection of building structures, especially bridges, is currently made by visual inspection. The few non-visual methodologies make use of wired sensor techniques, which are relatively expensive, vulnerable to damage, and time consuming to install. Systems based on wireless sensor networks should be both cost efficient and easy to install, scalable and adaptive to different type of structures.

Acoustic emission techniques are an additional monitoring method to investigate the status of a bridge or some of its components. It has the potential to detect defects in terms of cracks propagating during the routine use of structures. However, acoustic emissions recording and analysis techniques need powerful algorithms to handle and reduce the immense amount of data generated. These algorithms are developed on the basis of neural network techniques and – regarding localization of defects – by array techniques. Sensors with low price are essential for such monitoring systems to be accepted. Although the development costs of such a system are relatively high, the target price for the entire monitoring system will be several thousands Euro, depending on the size of the structure and the number of sensors necessary to cover the most important parts of the structure. Micro-Electro-Mechanical-Systems and hybrid sensors form the heart of Motes (network nodes). The network combined multi-hop data transmission techniques with efficient data pre-processing in the nodes. Using this technique, monitoring of large structures in civil engineering becomes very efficient including the sensing of temperature, moisture, strain and other data continuously. In this paper, the basic principles of a wireless monitoring system equipped with MEMS sensors is presented along with a first prototype.

Introduction

Continuous structural health monitoring should provide data from the inside of a structure to better understand its structural performance and to predict its durability and remaining life time. In particular acoustic emission (AE) measurement will be examined due to its ability to warn of crack growth and its mode. For example, railway bridges must contend with higher axle loads and higher train speeds [1] than expected during construction. Another example are structures exceeding the designed life time. In Europe, many structures originate from the middle of the last century, replacing structures destroyed during the Second World War. Concrete structures are typically designed for a 50- to 80-year life, which will soon be reached. The sudden collapse of a training hall in Bad Reichenhall (Germany) in early January 2006 with the loss of 15 lives and the collapse of a new trade building in Katowice (Poland) several weeks later – more than 60 lost their lives – demonstrated these problems drastically.

This leads to the conclusion that structures need a monitoring and inspection procedure which is reliable and inexpensive and easy to implement. The techniques used should be easy to adapt to different types of structures and structural parts since a large variety exists and adaptation is time consuming. From this background the authors strongly recommend development and application of wireless techniques based mainly on the use of micro-electromechanical systems [2].

1. Applied Techniques

1.1 Wireless Monitoring Techniques Based on MEMS

Existing monitoring systems use traditional wired sensor technologies and several other devices that are time consuming to install and relatively expensive (compared to the value of the structure). Typically they are using a large number of sensors (i. e. more than ten) which are connected through long cables and will therefore be installed only on a few structures. A wireless monitoring system with MEMS (Micro-Electro-Mechanical-Systems) could reduce these costs significantly [3-5]. MEMS are small integrated devices or systems combining electrical and mechanical components that could be produced for about 50 € each. The principle of such a system is shown in the scheme given in Fig. 1.

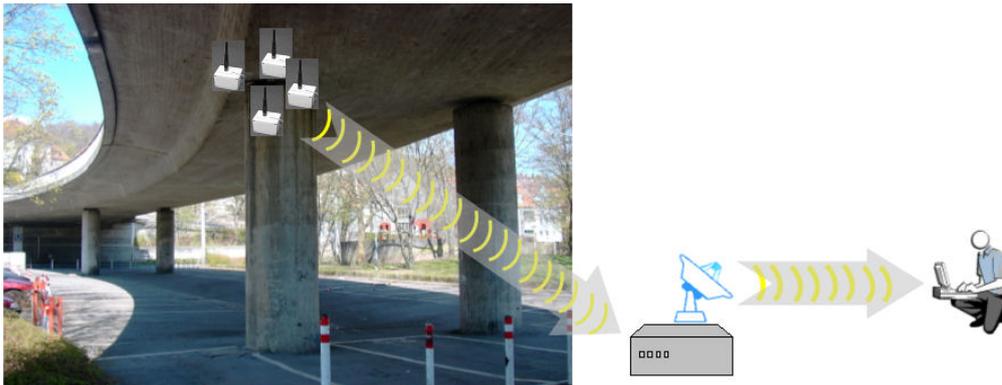


Figure 1: Scheme for wireless sensing of structures using radio frequency transmission techniques and MEMS [3]. Data are sending from the base station to the supervisor using e.g. internet or SMS protocols

1.2 Motes

Currently, a wireless sensor node with MEMS sensors could be fabricated at a price varying from 100 to about 400 € and future developments show the potential for prices of only a few Euro. Monitoring systems equipped with MEMS sensors and wireless communication can reduce the costs to a small percentage of conventional monitoring systems, and will increase its field of application. Due to the detailed information of the structural behavior of bridges obtained from the monitoring system, maintenance costs could also be reduced, since inspection methods [6] can be applied more efficiently. Only after certain changes in the structural behavior have been identified, will inspection (either by means of non-destructive testing [7] or visual methods) be necessary, and proper repair could be done immediately after the occurrence of the defect. This reduces the risk of further damage.

The analysis of measured data and the knowledge of continuous changes of structural behavior will improve the life time prognosis of civil structures, and reduce the overall maintenance costs of buildings and transport networks. Data has to be continuously

transmitted (e.g. using the internet or SMS protocols) to the supervisor. Each sensor device (mote), which is itself a complete, small measurement and communication system, has to be powered and cost optimized. Using multi-hop techniques, the data of the sensor network can be transmitted over short distances of some 10 m from each hop to a base station on site. At the base station the data items are collected and stored in a database for subsequent analysis. This data can then be accessed by a remote user. If the central unit detects a hazardous condition by analyzing the data, it raises an alarm message. The central unit also allows for wireless administration, calibration and reprogramming of the sensor nodes in order to keep the whole system flexible. Each mote is composed of one or more sensors, a data acquisition and processing unit, a wireless transceiver and a battery power supply (Fig. 2, right) [8]. The acquisition and processing unit usually is equipped with a low power microcontroller offering an integrated analogue to digital converter (ADC) and sufficient data memory (RAM) to store the measurements. This unit also incorporates signal conditioning circuitry interfacing the sensors to the ADC. In the following sections, some components are mentioned, but a more detailed description is given elsewhere [9].

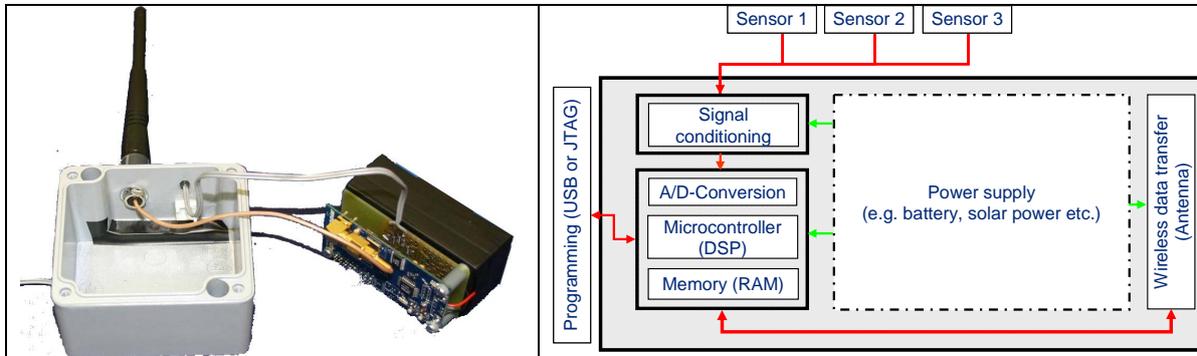


Figure 2: Principle of a MEMS based *mote*. Left: Mote (© Smartmote) including sensor and data processing board, radio transmission unit and antenna, container. Right: Concept of the sensor and processing board

Using this concept main issues arise dealing with power supply, proper sensing technique and network protocols as well as data transmission. Details are included in a recent paper published by some of the authors [10].

2. Application and data analysis

Structural health monitoring (SHM) deals with the more or less continuous recording of data obtained from several parts of the structure. Based on the experience of the constructor, owner, or inspector the regions where data are obtained can be restricted. In many cases it is necessary to just detect a deviation of the “usual” behavior of the structure, i.e. an outlier in a time-series. It is obviously very helpful not to base this analysis on one physical quantity alone or on one sensor. The reliability of the monitoring system is fairly enhanced combining the information obtained at different sensor nodes. Further on, comparison of time series obtained by recording different physical quantities results in a drastic improvement of reliability and lowers the detection threshold of deterioration. Establishment of a correlation between data and structural performance is difficult and should be based on the data interpretation expertise of the user, implying a natural application of Bayesian statistics. This combination can be done even in terms of a pre-processing of data in the mote or in a cluster of motes. This is the main advantage to telemetric systems using all the data. Intelligent data processing in the motes or clusters, enables pattern recognition algorithms which can additionally reduce the power

consumption. Only meaningful data are transmitted to the sink.

2.1 SHM using combined sensor information and clusters of motes

It is expected that the correlation of the recorded AE data with the data obtained by each sensor (temperature, humidity, strain, etc.) will lead to further understanding of structural behavior. For example a cross-check of AE activity with increasing strain or with a sudden or abnormal increase of the ambient or inner structure temperature can give further insight into structural state. Such sensor data correlations will also decrease the amount of data transmitted after implementing intelligent data processing and correlation algorithms.

Data analysis techniques based on the signal wave form will be included in future (e.g. [11-12]). Algorithms have been developed regarding energy-based techniques and techniques analyzing signals in the frequency/time, frequency/wavenumber or wavelet/time domain. Implementation of these techniques in motes must account for digital recording techniques, the sensor characteristics and the coupling of the devices to the structure, as well as power consumption. To give an example it is recommended to minimize the data transfer through the radio module which means that signal processing and data analysis should be done in the mote as far as possible. However, the signal analysis could be made by software or a DSP or FPGA that can perform a 1024-point FFT at 3.1 μ J using a 1.1 V supply.

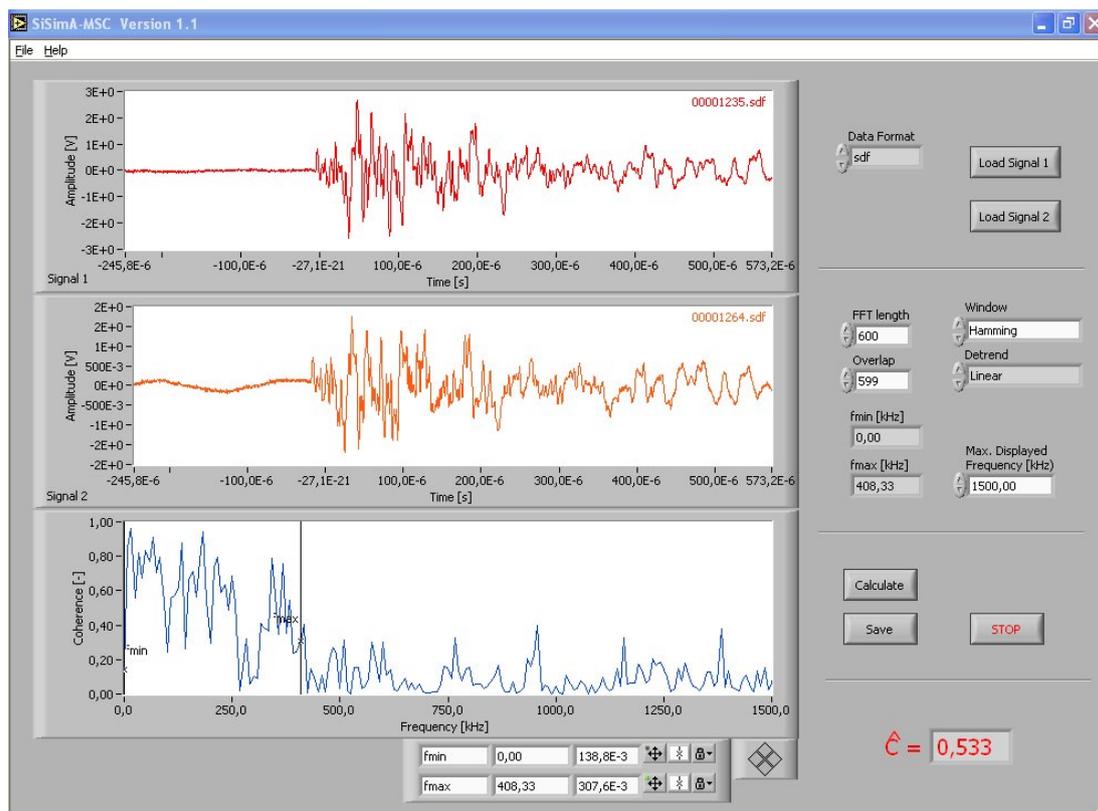


Figure 4: Example of similarity analysis techniques. Signal 1 (upper graph) is similar to the second signal (middle) and the MSC analysis (bottom) results in a fairly high similarity value \hat{C} of 0.533 [13]

In addition to the local signal processing running on a single mote, information within clusters can be aggregated in intermediate nodes, further processed, and forwarded as needed in compound packets to save energy. Such data aggregation and data reduction methods are needed to minimize the data traffic if the monitoring system consists of a high

amount of motes. First storing a set of data in a given sensor mote and then sending it consecutively through the radio module at specific time intervals, or events on request, will also improve the reliability of data transfer because the transfer can be specifically controlled. The need for cluster formation and management is also motivated by power consideration concerns as well as by the necessity of deciding whether or not an event is related to a structural defect or change in structural behavior. These clusters need to organize themselves.

2.2 Acoustic emission techniques for structural health monitoring

The most common passive monitoring system involves acoustic monitoring, most commonly called acoustic emission (AE). Acoustic emissions are elastic waves generated in conjunction with energy release during crack propagation and internal deformations in materials. Micro-structural changes or displacements occur very rapidly and can be produced by a wide variety of material responses to stress changes, from small scale changes within a crystal lattice structure to growth of macro-cracks. As stress waves propagate through a medium, the waveform shape is formed by the characteristics of the source, and affected by properties of the host material, and eventually the geometry of the host medium.

The primary tasks of an implemented AE system in wireless sensor networks consists of signal detection, denoising, localization and other data analysis and signal characterization techniques as described in the following. This document does not details of the data interpretation, because this will follow in another paper describing field tests. However, the interpretation will presumably be limited to an indication of a “zone of interest” further investigated by methods developed in and interpretation techniques based on results of ongoing work.

2.2.1 Signal detection

The discrimination between noise and signals (from structure deterioration) is essential for failure monitoring. The environment (railway bridges) is assumed to be very noisy. A noise analysis must be conducted using conventional hardware and sensors (broadband sensors) to characterize the frequency bands of noise at different bridges. This could be done during field tests at concrete, masonry and steel bridges separately.

Algorithms to discriminate between signal and noise have to be developed and to be implemented into the motes. It is assumed that the AE signal form is governed by travel path effects which overpower signals from the fracture process, enabling for simple discrimination techniques.

- a. Cross-correlation: Laboratory tests showed that the cross-correlation of signals originating from similar parts of a structure show a high correlation. Based on detailed knowledge of the structure, certain regions can be monitored directly by storing in memory the values of cross correlation between the actually recorded signal and a reference signal which is permanently stored in the EPROM called “signal squared coherence” (Fig. 4), giving a simple figure of signal similarities [13]. Only the correlation coefficient (coherence value), the event time and the “name” of the mote recording it have to be transmitted wirelessly. In the central processing unit a correlation of these data with real coordinates can be done. If several “hits” are recorded an alarm message can be transferred to the operator.

- b. Using the noise characteristic onsite as well as the amplitude attenuation due to geometrical spreading, a simple frequency transform can be used to discriminate signals from noise. This technique can be combined with simple threshold triggers and the method described under a.

2.2.2 Denoising

If AE signals are significantly affected by electronic or other noise, procedures called denoising have to be applied. Unfortunately, these techniques are usually calculation intense and therefore increase power consumption. Simple denoising techniques include bandpass filtering prior to data analysis. This can be done using proper hardware. If this is not sufficient, more sophisticated wavelet based filters can be applied which are under development [14]. These developments optimize the code in terms of power consumption.

2.2.3 Waveform Analysis

The wave motion transmitted by AE through the host medium contains information about the location and kinematics of the deformation (i.e. damage) taking place inside. By transducing and recording a suite of unadulterated particle motions in a three dimensional array relative to the internal dislocation, inversion theory can be used to identify the source kinematics [15; 16]. The fidelity of the sensor used is critical to quantitative AE analysis since the strain history must be accurately transformed into an electronic signal for any meaningful analysis to be carried out. Quantitative interpretation of AE signals start from a simple localization of the source coordinates of the AE, originating from a fracture or perhaps the relative motion of rebar and concrete. Simply using unambiguous first arrival of the primary (and/or secondary wave) can provide source kinematics through moment tensor inversion (e.g. [17-19]). Finally, an initial length of the waveform - from primary wave to surface wave arrival - can be used to perform a higher order inversion to yield full source kinematics (e.g. [11]; [20]). These techniques allow the user to qualitatively “peer into” the structure being monitored and identify the damage taking place to determine the actual condition so that preventative maintenance can be rationally applied.

2.2.4 Localization

There are diverse techniques for AE localization using completely different algorithms and assumptions. It is essential to know all existing solutions and to apply the most appropriate. For this reason a rough compilation of existing methods should follow. More details can be obtained from the literature in preparation [21]

- a. The roughest localization method is guessing the source origin using the “first hit” technique. The advantage of first hit techniques is that no sensor arrays and no data analysis are necessary. The sensor which detects an AE first defines a radius or a half sphere, respectively, in which the signal originated. Experience tells whether that technique is accurate enough. This can be done for some cases probably in combination with techniques described under section above or with knowledge from bridge inspectors to “localize” the source of failures.
- b. More sophisticated methods use planar techniques by recording AE signals at more than two sensors at the same time. This method requires time synchronization of the nodes and communication between nodes. More suitable techniques are beamforming for localization, described in the literature [10]. It should be stressed that 2D and even 1D localization can work well when used together with a priori information obtained from the construction plans or from the inspector of the bridge.

- Traditional 3D-localization techniques [19; 21] are not implemented in wireless sensor networks because of processing time and power consumption from inter-array communications. In many cases, the signal-to-noise ratio is not good enough to apply 3D-localization.

Other (probably more promising) options are methods based on array techniques. Since sensor arrays are successfully used in seismology, array data analysis techniques were implemented in the described SHM nodes. These techniques are now under test, requiring only data communication between nodes in a cluster. More details can be found in the literature [10].

4. Conclusions

The inspection of building structures is currently a visual process. Therefore, the condition of the structure is examined from the surface and the interpretation and assessment is based on the level of experience of the engineers. An approach to continuous structural health monitoring techniques based on wireless sensor networks were presented, which provide data from the inside of a structure to better understand its structural performance and to predict its durability and remaining life time.

A wireless sensor network system based on MEMS and hybrid sensors is developed by a team of scientists from different institutions/companies (IWB, UC Berkeley, Smartnode). The network is equipped with nodes and will be available for a very low budget. Since prototypes are already available, the system is now undergoing an optimization process regarding power consumption, data acquisition and data aggregation, signal analysis and data reduction [9].

Acoustic emission techniques can play a significant role for the monitoring of civil engineering structures since they are able to reveal hidden defects leading to structural failures long before a collapse occurs. However, most of the existing AE data analysis techniques seems not be appropriate for the requirements of a wireless network including distinct necessities for power consumption. The authors suggested with this paper approaches using array techniques. First tests showed promising results for both, reliable AE data analysis as well as power saving processes. Further developments based on this approach will show the efficiency of the suggested techniques.

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