Sensing methods in civil engineering for an efficient construction management

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Abstract: Sensing methods including Non-destructive testing and monitoring techniques are fundamental tools for performing an efficient condition management system for structures in service. They can on one hand support regular visual inspections and help on the other side to assess the actual condition and performance of a building. These methods provide reliable data for the stakeholders to estimate the necessity for current and future investments into a structure.

The main purpose of a monitoring system in civil structures is to support activities of engineers in doing structural assessment. A monitoring technique which is presented consists of a wireless sensor network using different types of sensors including MEMS. Wireless sensor networks (WSN) can be used to monitor a certain region of a structure providing data about different physical measures. Some properties to be measured in-situ are the Eigenvibrations of the structure, humidity and temperature outside and inside the structure, unusual stress and strain, and the detection of cracks and other deteriorations. An embedded sensor system is developed to acquire the structural condition and a wireless network propagates the sensor data towards a common base station where further analysis is performed.

Keywords: Non-destructive testing, monitoring, structural health, sensing, public private partnership contracts

Introduction

Continuous structural health monitoring should provide data from a structure to better understand its structural performance and to predict its durability and remaining life time. In particular, the understanding of the structural performance becomes important at bridges that are more and more confronted with higher axle loads and higher train speeds as well as an increase of overall traffic due to the enlargement of the European Union. In this context a European Research Project was approved in the Sixth Framework Programme called “Sustainable Bridges - Assessment for Future Traffic Demands and Longer Lives” [2007] where, among others, the Institute of Construction Materials of the University of Stuttgart is involved.

Another goal for an efficient monitoring approach to structures is safety. In Europe, many structures originate from the late 40ies or 50ies of the last century replacing structures destroyed during the Second World War. Many concrete bridges are designed for a typical lifetime of 60 to 80 years, what is reached or will be reached soon. Same is true for public buildings that were build using a variety of materials and material compositions. 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.

Finally, not only existing buildings are subjected to monitoring but also the construction process itself. Previously the contractor simply implemented a given design, but the current trend is for clients to commission certain performance requirements to be met with performance-based design. The emphasis of the industry is becoming the delivery of certain structural behavior states rather than simply building to a client’s plan. The contracting process becomes the determination of the performance criteria, and delivery becomes a long-term fulfillment of these criteria. This can only take place if the performance states can be measured, and the measurement utilizes in a decision making process. The tools needed for both the evaluation of the delivery after construction and during operation are changing accordingly. The process is increasingly dependant on densely spaced sensor data, valid models to turn the data into physical behavior and decision making tools to determine whether the performance requirements are being met. Regarding proper sensing techniques there are new aspects of measuring structural performance and convert sensor data into useful information needed by stakeholders.

Basics of monitoring performance-based structures

In a performance-based approach to build structures, all decisions, choices, and tradeoffs start with the required behavior-in-use rather than prescribed solutions for how to meet the stated needs. The supplier responds with an offering that includes the estimated performance of that offering. A validation method, through measurement, calculation, or testing, is necessary to evaluate the performance (over time) and to compare alternative solutions [Szigeti & Davis, 2005]. The design/build team must warrantee and maintain structural performance to the level stated in the contract, for the extended duration of the contract. How that performance is established, verified and validated, is one of the areas that need further research. This requires measurement, hence sensors. This scenario opens a new perspective for overall optimal life-cycle management. A client may wish to measure the output values of ready made constructions; a contractor – on the other hand – may demonstrate the compliance to the required performance. The facility manager starts utilizing the performance data to optimize operation-phased maintenance and economy. Proactive interventions can be made when performance indicators start to deviate [e.g. Yanev, 2003]. Alarms can be generated based on deviations in the performance data, and repair plans augmented with actual real time data. The obvious needs for sensor generated data describe the reason for many efforts recently made to establish an entire new category of performance and condition monitoring services.

Sensors, MEMS and motes

Traditionally the term sensor has been synonymous with transducer. However, a “sensor” will here be defined as comprising the traditional transduction elements along with substantial signal processing and computational ability [e.g. Glaser et al. 2005]. These sensors can also be combined into comprehensive miniature sensing platforms incorporating transduction, signal processing, computational power, and wireless communication – platforms that are called Motes [e.g. Krüger et al. 2005; Grosse & Reinhardt 2007] (Fig. 1, left).

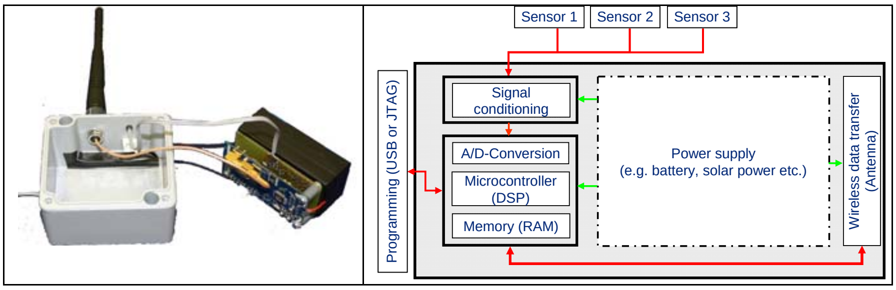


Fig. 1: Principle of a *mote*. Left: *Mote* including sensor and data processing board, radio transmission unit and antenna, container. Right: Concept of the sensor and data processing board

Such a node is a complete, small measurement and communication system that has to be powered and cost optimized. composed of one or more sensors, a data acquisition and processing unit, a wireless transceiver and a battery power supply (Fig. 1, right). 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.

Almost all types of sensors can be attached to such a sensor node as long as the power consumption is in relation to the purpose of the sensing system. Low-power sensors are first choice and that is the reason why micro-sensors called MEMS (micro electro-mechanical systems) are very attractive to be combined with such a system. MEMS are small integrated devices combining electrical and mechanical components that could be produced for about 50 € each. Because the process elements and internal linkage movements are now small, these MEMS-based transducers consume very little power. The low cost, low power and small size of MEMS-based transducers have revolutionized the way we can measure. This includes also the combination of sensor data and the formation of networks of sensors as well as combination with low power video techniques (VSLI cameras).

Sensor networks and protocols

Wireless sensor networks consist of many nodes (motes) having one or several different sensors on board. After the recording and a preliminary analysis of the data in the mote, the data has to be transmitted using, for example, a radio transmission system to a base station or supervisor for further data processing or proper generation of alarm messages. For the transmission of data using sensor nodes in a network of motes several topologies exist including the star and the multi-hop topology [Culler et al. 2003].

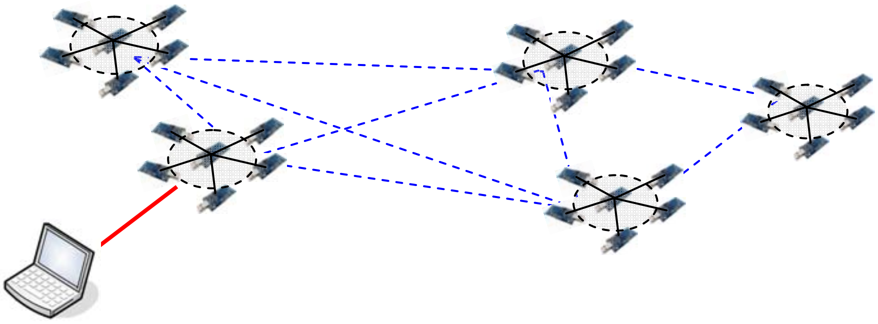


Fig.2: Scheme of a multi-hop sensor network using clustered sensor nodes

The main advantage of multi-hop techniques are the transmission power efficiency, because only a fraction of energy is necessary to transmit data compared to other techniques; the data are transmitted just to the next nodes and not necessarily to the sink. This reduces also the danger of interference since a node communicates only with a few others. However, this requires sophisticated network protocols including ad hoc configuration capabilities as well as self-configuration, calibration and encryption. As a next step we have implemented a clustered multi-hop technology. Motes in a cluster (marked with a dashed circle in Fig. 2) share the data of all sensors attached to these motes. A pre-processing of the data is done in the cluster prior to transmission via the other clusters in the multi-hop network to the data sink (symbolized by the laptop in Fig. 2). This is the main advantage compared to telemetric systems where all data are transmitted. 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. The data sink is further extracting information out of the data using knowledge-based algorithms sending afterwards the information to the responsible person (construction engineer, owner) using automated email messages or short message systems of mobile phones.

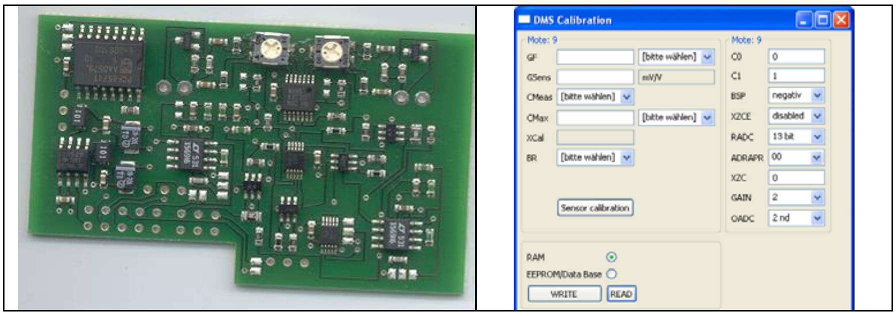
A sensing system based on wireless motes has several more advantages. Such a system is easy and cost efficient to be applied to structures. It can be used on one structure for a while and when or if the stakeholder decides to have enough data collected at this particular structural part the system can easily be deployed somewhere else. Additionally, a variety of sensors can be used to get information about the status of the structure. It is obviously very helpful not to base a structural health analysis on one physical quantity alone or on one sensor. The reliability of a 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. Embedding some local processing capabilities within the sensor networks is desirable. For example, the temperature data gathered from numerous sensors could be fed into one or more other sensors on the network for processing. A weighted average could then be calculated and transmitted to the user, significantly reducing the amount of data flying around the network.

Finally, two other advantages of wireless sensor networks have to be stressed. Scalability can be an issue if the stakeholder wants to extend the monitoring area or need more data. Existing WSN techniques enables for self-organization of such networks so that sensor nodes can added or removed at any time without time consuming user guided reorganization of the WSN. Additionally, the implemented preprocessing algorithms might need an update from time to time to adjust to the user requirements or for a more efficient data reduction. Most of the developed sensor nodes have the capability to be reprogrammable, i.e. that the user can change the algorithms implemented in each sensor with the press of a button.

However, MEMS sensors are not available for all kind of applications regarding structural health monitoring in civil engineering. Therefore, sensor nodes are developed to enable *motes* to communicate with conventional sensors as well, i.e. in addition to MEMS. These sensing techniques are called hybrid sensor nodes. Although these sensors are low-power sensors, they will partly be replaced by MEMS as soon as they are available.

Hardware developments

Separate boards for signal conditioning of strain and piezoelectric data (like acoustic emissions) have been developed by the University of Stuttgart with the help of EMPA (Eidgenössische Materialprüfanstalt, Switzerland). Implementation and development of the electric components, layout as well as manufacturing of prototypes is in progress. The boards are developed for a rough environment what included the implementation in sealed containers following the IP64/65 standards of water protection. As an energy source a high capacity 18 Ah battery was chosen at this stage of the project keeping in mind that it should be replaced by other techniques (solar power, energy harvesting techniques) depending on the application. In addition to the strain and piezoelectric data the ambient temperature and humidity can be measured by MEMS sensors implemented in the motes. A signal conditioning board for strain gage measurements was developed (Fig. 3) with the option of two parallel strain measurements at the same time. The board enables a full front-end for resistive sensors with temperature compensation, calibration and linearization (Fig. 4, right).



GF: [bitte wählen]
GSens: mV/V
CMeas: [bitte wählen]
CMax: [bitte wählen]
XCal:
BR: [bitte wählen]

C0: 0
C1: 1
BSP: negativ
XZCE: disabled
RADC: 13 bit
ADRAPR: 00
XZC: 0
GAIN: 2
OADC: 2 nd

RAM ●
EEPROM/Data Base ○

Fig. 3: Signal conditioning board for strain and developed graphical user interface

Also a signal conditioning board for piezoelectric sensors was developed consisting of two channels per board with the opportunity to implement two boards in one sensor node. Each of the 4 channels can be filtered (high pass) and amplified individually. Antialiasing filters can be applied and a triggered recording of events is possible. Several modi to reduce the energy consumption are implemented as well. The A/D conversion is done using the TI microcontroller MSP430 from the mote. Comfortable user interfaces (GUI) were developed to control the devices. For first tests only one channel was used for acoustic emission (AE) monitoring (Fig. 4, left).

Monitoring bridges using wireless sensing techniques

As a first test the equipment was installed for wireless measurements of strain and acoustic emissions during load at a large test facility (Fig. 3) of the Technical University of Braunschweig, Northern Germany, and at a smaller structure of the University of Stuttgart. Since not all data of the large test are yet analyzed the test procedure of the small scale test as well as the implemented techniques will be described in the following.

The most common passive monitoring system involves acoustic monitoring, most commonly called acoustic emission (AE) [Grosse, Wanner et al. 2006]. 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.

Fig. 4: "Concerto Bridge" in Brunswick equipped with wireless AE sensors (left) and with wireless strain sensors (right)

The primary tasks of an implemented AE system in WSN consists of signal detection, denoising, localization and other data analysis and signal characterization techniques as described in the following. This document does not give 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. 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 behaviour. 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.

Signal detection

The discrimination between noise and signals (from structure deterioration) is essential for failure monitoring. The environment (e.g. 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. They could be based either on Fourier transforms or cross-correlations calculating the Magnitude Squared Coherence for example [Grosse, Glaser et al. 2006; Grosse & Reinhardt 2007]. It is assumed that the AE signal form is governed by travel path effects which overpower signals from the fracture process, enabling for discrimination techniques. Denoising techniques and a waveform analysis can also help to detect signals and discriminate them.

Localization

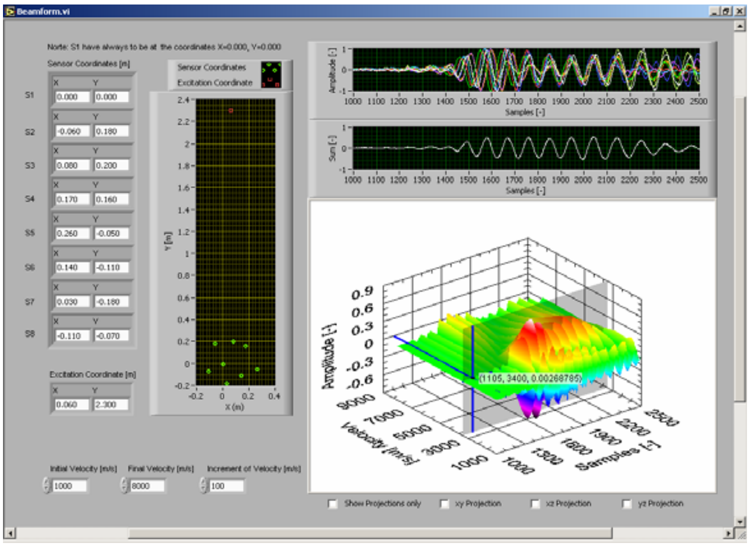
There are diverse techniques for AE localization using very different algorithms. Most of the existing solutions are described elsewhere [Grosse & Ohtsu 2007]. Using AE techniques at CE structures for monitoring rough and robust techniques are necessary like the “first hit” technique or planary techniques calculating 2D source coordinates. Traditional 3D-localization techniques 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 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 motes. These techniques are now under test, requiring only data communication between motes in a cluster.

Acoustic emission array techniques

Acoustic emission experiments at a reinforced concrete bridge in Stuttgart-Vaihingen have been set up to test and implement wireless acoustic emission techniques and in particular AE array techniques including localization, filtering (using wavelet techniques among others), beamforming, *f*-*k*-analysis, *VESPA*-processes.

Fig. 5 Overview of setup for wireless AE measurements at the Stuttgart “ramp” (left) and wireless AE array setup (right)

A non-regular array consisting of eight wireless AE sensors was set up using the piezo-board described above. Several routines were developed to record and establish robust data processing of acoustic emission data in the nodes. The recording and pre-processing in the motes was tested with a self-written GUI [Fig. 6]. Artificial AE sources (“Hsu-Nielsen source” that is a procedure according to ASTM to break pencil leads) were used to test the soft- and hardware. These signals were recorded in up to ten meter distance from the central point of the array. Beamforming algorithms for AE signal detection were implemented similar to techniques used recently for data transmission in WLAN networks (IEEE 802.11n standard). Some features of these algorithms are described in the following section.



Note: S1 have always to be at the coordinates X=0.000, Y=0.000

Sensor Coordinates [m]

	X	Y
S1	0.000	0.000
S2	-0.060	0.180
S3	0.080	0.200
S4	0.170	0.160
S5	0.260	-0.050
S6	0.140	-0.110
S7	0.030	-0.180
S8	-0.110	-0.070

Excitation Coordinate [m]

X	Y
0.060	2.300

Initial Velocity [m/s] 1000
Final Velocity [m/s] 8000
Increment of Velocity [m/s] 100

☐ Show Projections only ☐ xy Projection ☐ xz Projection ☐ yz Projection

Fig, 6 Automatic recording and localization (left part of the figure) with red dots (green dots are the 8 sensors of the array) as well as the result of the beamforming for a certain triple point in the VESPAgram (see below)

Beamforming

A further step to apply acoustic emission analysis in a WSN is the implementation of beamforming techniques. Beamforming can be used to improve the signal-to-noise ratio of direct compression waves from known sources. It can furtheron be used do detect certain coherent signal phases if two or more are crossing the array and have to be discriminated. Finally it is useful for a rough localization of events. The principles of array techniques have been first developed for applications in electrical engineering e.g. for antenna or microphone arrays. In seismology, similar techniques were developed for the nuclear test ban treaty to monitor unusual seismic activity possibly originating from underground nuclear explosions.

The signal-to-noise ratio of a signal can be improved by stacking the coherent signals from each sensor after correcting for the different arrival or delay times. Therefore, the most important point during array beamforming is to find the best delay times for shifting the individual signals. A detailed description of the slowness can be found in the literature [Shearer 1999] while first ideas about application of these techniques are described in Grosse, Glaser et al. [2006] and in Grosse & Reinhardt [2007].

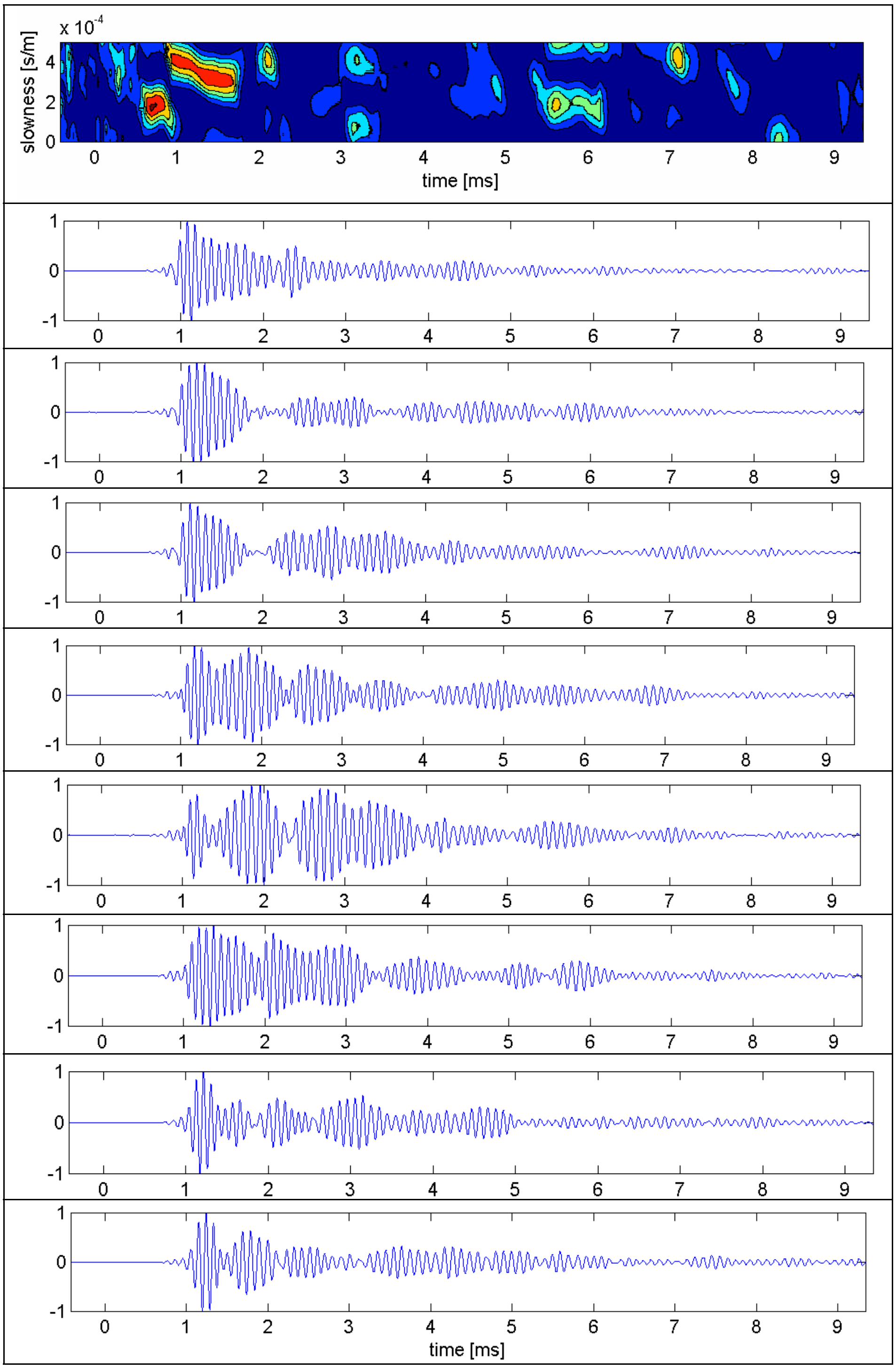


Fig. 7 **Example of the detection of different wave types (compressional and surface waves) in the AE recordings of an eight channel sensor array using a weighted SN-VESPA process (diagram above the channels)**

In the case that each channel (single-sensor recording) of an event is properly shifted in time for a certain back azimuth and slowness, all signals with the matching back azimuth and slowness will sum constructively. If more than one array is used a two-dimensional localization of the source of the incident wave is possible by calculating the point of intersection of at least two back azimuth lines in the plane of the sensor array. Beamforming techniques can also be applied to discriminate for a certain wave phase. This is useful to detect wave modes hidden by reflected waves or in the coda of a preliminary wave or simply to discriminate between compressional and surface waves. For phase detection a 3D iteration problem has to be solved, iterating signal time, slowness, and amplitude. Visual analysis can be done by generating a graph in the slowness-time domain, as shown in Fig. 8. This example shows that phases with lower slowness of about $2*10^{-4}$ s/m arrives first at the array sensors than phases with a slowness of about $4*10^{-4}$ s/m. The first wave front with smaller amplitude is representing the compressional waves generated by the source traveling with a velocity above 4000 m/s. This phase is difficult to be detected in the time domain recordings at each sensor (eight traces in the lower part of Fig. 7). The slower wavefront following a few microseconds later with much larger amplitudes and a velocity around 2400 m/s is indicating the arrival of surface waves generated by the same source. Both wave types clearly are discriminated by using a novel developed relative S/N-VESPA (VElocity SPectral Analysis) technique (see upper part of Fig. 7) that will be described in another paper. Out of such a graph it is easy to determine the optimum slowness for the delay and sum method for each phase (wave).

Conclusions

Condition control of building structures is a fundamental aspect in structural assessment business. In doing so NDT techniques are in principle applicable. Often the interpretation of condition control data is highly based on the level of experience of the engineers. To supplement the current inspection practice with a wireless sensor network system based on MEMS and hybrid sensors is currently under development. The network is equipped with motes 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.

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 these techniques.

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