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Acoustic emission localization methods for large structures based on beamforming and array techniques

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Abstract

The inspection of bridges is currently made by visual inspection or by wired sensor techniques, which are relatively expensive, vulnerable to damage, and time consuming to install. In contrast, wireless sensor networks are easy to deploy and flexible in application so that the network can adjust to the individual structure. Different sensing techniques can be used with such a network, but acoustic emission techniques have been rarely utilized. With the use of acoustic emission (AE) techniques it is possible to detect internal structural damage from cracks propagating during the routine use of a structure or the break of wires of pre-stressed elements for example. Most of the existing AE data analysis techniques are not appropriate for the requirements of a wireless network, especially regarding power consumption, memory storage or time synchronization.

New algorithms have been developed using a new concept called Acoustic Emission Array Processing. As a first step, beamforming and source discrimination techniques were tested as well as a method based on a modified velocity spectral (VESPA) process. Traditional signal-based acoustic emission techniques include a two or three-dimensional localization of AE events based on the time difference of arrival (TDOA) technique using at least eight sensors that have to be placed well-distributed around the hypocenter, i.e. the AE source. The array concept allows for much simpler localization techniques with less hard- and software efforts. The beamforming method calculates the azimuth of the waves impinging on a small array of sensors by steering the beam through a range of azimuths until the steered delays match the observed time delays. This formulation operates under a different set of assumptions than the TDOA method and does not require the determination of any P wave arrival times. In fact, it doesn't require the detection of a P wave at all. The direction of arrival can be determined simply from the relative time delays of Rayleigh waves (R-waves).

Résumé

L'inspection de ponts est actuellement mise-en-œuvre par inspection visuelle ou par des techniques câblées, qui sont relativement onéreuses, vulnérables et prenant longtemps pour leur installation. En revanche, le déploiement de réseaux de capteurs sans fils est simple et flexible en ce qui concerne leur application de sorte que le réseau puisse s'ajuster à la structure individuelle. Différentes techniques de capteurs peuvent être employées avec un tel réseau, mais des techniques d'émission acoustique ont rarement été utilisées. Avec l'usage des techniques d'émission acoustique (AE), il est par exemple possible de détecter des dommages structuraux internes des fissures se propageant pendant l'usage courant d'une structure ou de la fissure des câbles d'éléments précontraints. La plupart des techniques d'analyse de données AE existantes ne sont pas appropriées pour les exigences d'un réseau sans fil, particulièrement en ce qui concerne la consommation d'énergie, le stockage de mémoire ou la synchronisation temporelle.

De nouveaux algorithmes ont été développés en utilisant un nouveau concept appelé traitement de champ d'émission acoustique (Acoustic Emission Array Processing). Dans un premier temps, des techniques de collimation de rayons et de discrimination de source ont été examinées tout comme une méthode basée sur un processus spectral de vitesse modifiée (VESPA). Les techniques d'émission acoustiques traditionnelles basées sur le signal incluent une localisation bi- ou tridimensionnelle des événements d'AE basés sur la technique de différence de temps d'arrivée (TDOA) à l'aide d'au moins huit capteurs qui doivent être bien distribués autour de l'hypocentre, c.-à-d. la source d'AE. Le concept de champ tient compte de techniques de localisation beaucoup plus simples avec des efforts moindres d'équipement et de logiciel. La méthode de collimation de rayons calcule l'azimut des ondes percutant un petit champ de capteurs en orientant le faisceau par une gamme d'azimuts jusqu'à ce que les délais orientés égalent les délais observés. Cette formulation fonctionne sous un ensemble de suppositions différentes de la méthode de TDOA et n'exige la détermination d'aucun temps d'arrivée d'onde P. En fait, elle n'exige pas la détection d'une onde P du tout. La direction de l'arrivée peut être déterminée simplement à partir du délai relatif des ondes de Rayleigh (ondes R).

Keywords

Acoustic emission analysis, array techniques, beamforming, localization, SHM, monitoring

1 Introduction

Acoustic emission techniques are difficult to be applied to large structures due to the huge area needed to be monitored, and the distortion of the waveforms after traveling through even a few meters. A conventional acoustic emission (AE) setup consists of many sensors distributed around potential source locations [1]. Arrival-time-difference techniques are used for hypocenter localization using complicated analysis routines, relying on accurate arrival time detection algorithms requiring exact time synchronization of the data acquisition system and sensors. This approach is on the one hand time and resources intense and in most cases not appropriate for AE applications concerning the monitoring of large constructions out of concrete, steel or wood. On the other hand is a high accuracy of the hypocenter determination also not necessary and a simple detection of deteriorations sufficient enough to trigger next actions. Simple identification techniques seem to be more appropriate to support the routine visual inspection than traditional NDT techniques.

This paper presents an approach using a much simpler way to setup sensors and to analyze the data. The array signal processing techniques of beamforming and VElocity SPectral Analysis (VESPA) is brought to bear on data collected from simple arrays of inexpensive sensors. These techniques were originally developed for other fields but here expanded for the AE arena. The approach is in particular suitable to be used in combination with wireless sensor networks [2].

2 Array techniques and time delay beamforming

Beamforming is a method of sampling the elastic wave field in both space and time. Beamforming and other array processing techniques are well known in seismology [3], radar, and sonar. These techniques have also been used for nondestructive evaluation of materials, since beamforming can be used in active arrays to generate wave fields which are directed or focused on one particular location in space and time.

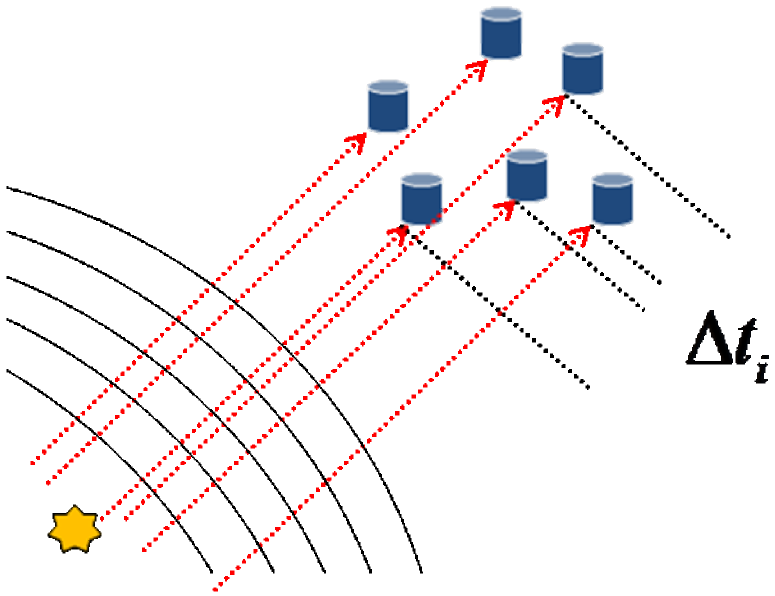

Figure 1. *Elastic waves radiated by an acoustic emission impinging an planar array of six sensors and arriving at each sensor with a certain time delay.*

Elastic waves emanating from a localized source such as a crack propagate outward with spherical wave fronts as shown in Figure 1. At large distances from the source, these spherical waves can be well approximated by plane waves. In beamforming array processing it is assumed that the wave field is constant across the wave front. Therefore, the signals received by neighboring sensors (in an array of *i* sensors), that has a sensor spacing which is small compared to the distance from the source to the sensors, will be delayed replicas of one another (signals plotted in Fig.2 upper right for the array plotted left). The amount of the delay (Δt_i in Figure 1) depends on the geometry of the array, the direction of the wave front and the velocity at which the wave front travels.

The beamforming array output is a function of the delays which are a function of expected properties of the stress wave field; the beamforming array output can be adjusted algorithmically to accept waves arriving at a given direction and at a given speed. This is known as 'steering' the array to a direction or 'focusing' it on a given wave velocity. This is shown in Fig. 2 lower right.

More examples of this array technique that can either be used to analyze different wave mode arrivals (P-waves, S-waves, and R-waves) or to determine roughly the azimuthal direction from where the signals hit the array are given elsewhere [4]. If the velocity of wave propagation is known, the incidence angle can be determined and vice versa. For most civil infrastructure applications such as bridge decks and walls, the angle of incidence is nearly 90 degrees (i.e. the source is nearly in the plane of the sensor array). In these cases source location can be considered a two dimensional problem and the slowness is very nearly equal to v-1. The azimuthal direction of arrival can be determined independently of slowness.

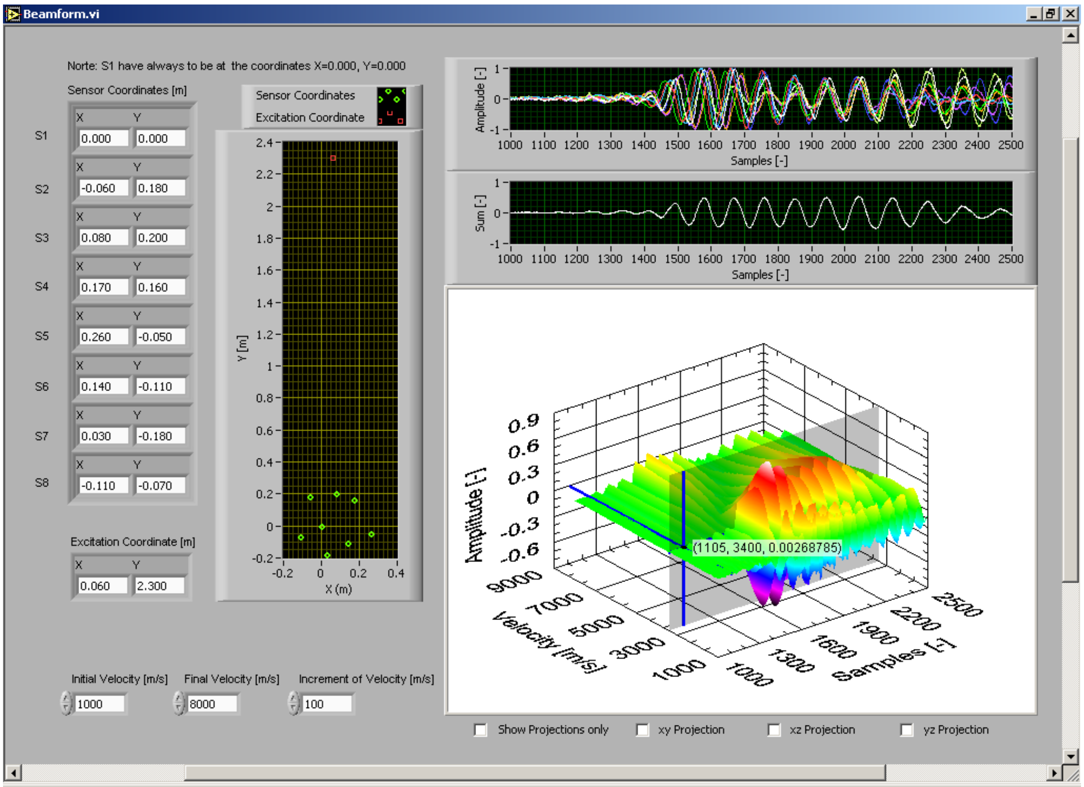

Figure 2. *Automatic recording and localization (left part of the figure) with red dots (green dots are the 8 sensors of the array) as well as the result of the beamforming for a certain triple point in the VESPAgram*

2.1 Effectiveness of array based acoustic emission techniques

Beamforming acoustic emission techniques are cost effective because they modify the method of acoustic emission to a form well suited for use with a wireless sensor network. Wireless sensor networks reduce costs because they are easier to install than wired systems, easily scaled to accommodate different types of structures, and reduce the need for expensive cables. The geometry of sensor arrays makes the requirements for time synchronization within an array easy to meet. In traditional acoustic emission, sensor configurations which rely of AE source location based on triangulation the sensors must be well distributed over the entire structure because only AE sources which are encompassed by the sensor array can be accurately located. This requires the use of many tens of sensors on a large concrete structure and perhaps km of shielded cables. Beamforming approaches use small aperture arrays (perhaps 200 mm in diameter and six to eight sensors) in which all sensors can be hard wired together to provide sufficiently accurate time synchronization. Furthermore, more than one beamforming AE sensor array (of 4-8 sensors) can be linked wirelessly and precise time synchronization (down to the µs) between multiple arrays is not required for source location estimates. Another reason beamforming AE arrays are suitable for wireless sensor networks is that they require less data transmission. In conventional AE monitoring arrival times and signal characteristics from each distant sensor must be sent to a main station for analysis. With beamforming AE, the analysis procedures described in this paper can be performed at the location of the small aperture beamforming AE sensor array, and the only information which will need to be sent wirelessly is the direction of arrival of the AE, the time of the AE, and possibly some consolidated array information such as the beamforming output or characteristics of a VESPA process. This concentration of information which must be sent wirelessly allows beamforming AE to be more power efficient.

3 First tests on large structures

As a first test, equipment was installed for wireless as well as wired measurements of crack opening and acoustic emissions during load at a large test facility made out of pre-stressed reinforced concrete (Fig. 3) called "Concerto" at the Technical University of Braunschweig in Brunswick, Northern Germany. It was constructed to investigate long-term behaviour and deterioration processes by continuous monitoring. In cooperation with the Universität Braunschweig, the test specimen was loaded at discrete intervals by manually driven hydraulic jacks so that concrete cracking at the midspan was observed.

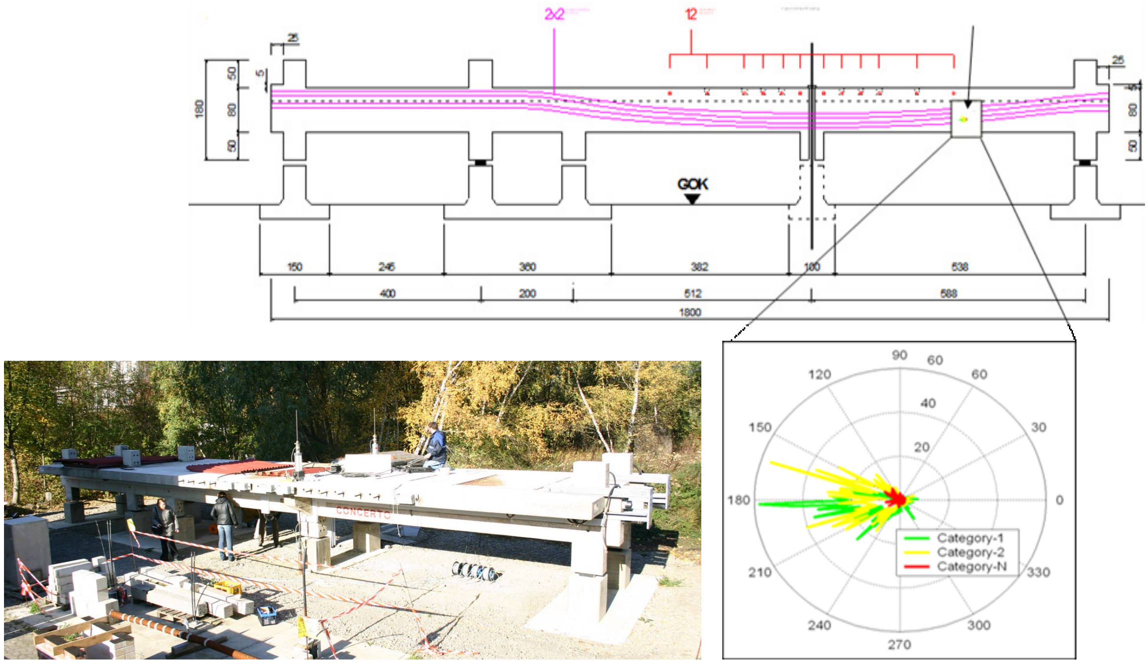

Figure 3. *Test bridge "Concerto" (left), setup (top) and result of Ae analysis including the determination of AE azimuths and classification of AEs*

During the bending test, acoustic emissions were recorded by two PC-based Transient-recorders and also by wireless sensors (Fig. 4, left) using a threshold trigger [5]. One transient recorder was used for the sensor array for testing beamforming techniques. The array used in this experiment was a cross-shaped array with eight sensors that was optimized to operate on signals up to 25 kHz. The number of events recorded is displayed in the lower right corner of Fig. 3 while the cracks were observed visually and marked for the time of the experiment as well as by wireless displacement sensors (Fig. 4, right).

Acoustic emissions were recorded using eight broadband ultrasound sensors. The sensor setup was optimized with respect to the frequencies of interest. Primarily this was done in order to obtain better resolutions and less interference using the conventional interpolation beamformers that were investigated. A total of 2458 datasets were recorded during the test with each dataset comprised of eight waveforms. The loading was introduced to the structure by hand driven oil pumps operated by a worker who was sitting on top of the structure. The manual operation caused several acoustic events that were also recorded during the test and representing acoustic emissions that are classified as pure noise or acoustic events strongly influenced by noise. Using time domain interpolation beamformers, the direction of the cracks could have been adequately estimated using adequate interpolations intervals [5].

Performance and computational complexity of the algorithms are in direct relation with the aperture size, the number of sensors and the interpolation intervals.

Figure 4. *Bridge equipped with wireless AE sensors (left) and with wireless displacement sensors (right)*

4 Conclusions

Condition control of building structures is a fundamental aspect in structural assessment business. To supplement the current inspection practice with a wireless sensor network system based on MEMS and hybrid sensors is the major goal of current activities [6]. 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 [1]. This is true also, if the defect already exists and monitoring techniques are applied at a later stage or if it is "healed" by post-hydration effects in concrete. The ability to monitor cracking and friction processes over a long period allows to detect changes in the status of a structure without the necessity to consider effects like the Kaiser of felicity effect in detail. However, most of the existing AE data analysis techniques seem not to be appropriate for the requirements of a wireless network including distinct necessities for power consumption. The author suggested with this paper approaches using array techniques and beamforming. 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.

Beamforming offers a promising step towards increasing the reliability of structural health monitoring systems for large civil structures while reducing the costs of such systems. Instead of relying on either qualitative, statistical measures of acoustic emission activity or costly sensor arrays which must encompass the expected location of acoustic emission sources, beamforming acoustic emission is a cost effective and elegant method of obtaining quantitative information from acoustic emission signals from one or more small arrays of 4-8 elements. Beamforming analysis procedures are based on simple delay and sum beamforming techniques which have been utilized for decades in a wide variety of applications ranging from sonar to seismology. From these analysis methods, the direction of the acoustic emission source can be reliably estimated and additional signal discrimination based on the arrivals of different wave types which propagate at different speeds can be attained via the VESPA process. The most promising feature of the beamforming acoustic emission method is its suitability to wireless sensor networks which will lower the cost of implementing this structural health monitoring method. Some example applications at structures will be presented.

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