Monitoring techniques based on wireless AE sensors for large structures in civil engineering

Christian U. Grosse; Florian Finck; Jochen H. Kurz; Hans W. Reinhardt

University of Stuttgart, Inst. of Construction Materials, Stuttgart, Germany

Keywords: acoustic emission, concrete, buildings, wireless sensors, MEMS

Abstract

Acoustic emission techniques (AET) are an alternative 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 occurring during the routine use of bridges.

Due to the attenuation of acoustic waves and geometrical spreading in concrete structures numerous sensors have to be applied to cover all critical parts. On the other hand a wired connection between all sensors and the processing facility is increasing the installation expenses in an inefficient way. These circumstances make the traditional way to apply AE techniques uneconomical.

It is suggested that a monitoring system for large structures should be based on a new kind of sensors using micro electro mechanical systems (MEMS) as well as powerful algorithms to handle the immense amount of data. Sensors based on MEMS are cheap and usually wireless in a self organizing network. Therewith critical structural points in a key building can be monitored during lifetime of the building without having any traffic-free time or expensive in situ observations by specialists.

The paper is giving an overview about modern data processing and analysis techniques and closes with an outlook to new monitoring techniques based on wireless sensors.

1. Motivation

Acoustic emission technique (AET) is considered quite unique among the non-destructive testing (NDT) methods. In contrast to other NDT methods, AET is usually applied *during* loading, while most others are applied *before* or *after* loading of a structure. For example the ultrasound method, which is a typical NDT technique, is able to detect the geometric shape of a defect in a specimen using an artificially generated source signal and a receiver, whereas AET detects the elastic waves radiated by a growing fracture.

There are numerous ways to apply AE techniques. Some reasons for its increasing acceptance are the advancements in microelectronics and in computer-based analysis techniques. AET is usually dealing with high signal rates and events at relatively high frequencies (from 20 kHz up to several megahertz). Recording and analysis devices need powerful techniques to handle these data.

2. Basics of signal-based acoustic emission

Failure processes of brittle specimen are accompanied by a sudden release of energy in the form of acoustic waves. Depending on the material and the stress regime failure consists of only one single transient event or is composed by a number of discrete cracks and micro cracks each producing an acoustic emission.
In contrast to parameter-based AE techniques, signal-based acoustic emission techniques are using the complete waveform of transient data. Transient AE signals contain a wealth of information about the fracture process and the travel path of the wave, which can not be extracted by simply storing parameters such as time of the signal exceeding a threshold, rise time or maximum amplitude. Signal-based acoustic emission analysis permits more detailed investigations and reveals an accurate localization of AE as well as information about the fracture type, its orientation, the energy released and other parameters describing the failure process. For an interpretation a wide range of inversion algorithms developed in seismology were adapted.
An accurate localization of acoustic emissions within a specimen can be performed from the onset times of compressional body waves (p-waves), when the propagation and the velocity of the p-waves are well known [GEIGER 1910; LANDIS ET AL. 1992; ONCESU & GROSSE 1998; GROSSE & REINHARDT 1999]. This technique was proofed in numerous applications [OHTSU ET AL. 1991; LANDIS 1993; GROSSE 1996; KÖPPEL & GROSSE 2000; KÖPPEL & VOGEL 2000; KÖPPEL 2002 ; FINCK ET AL. 2003].

Signal conditioning

AE events generated through crack formation are usually of low amplitude. Therefore, one goal of signal conditioning is the reduction of noise mixed up with signal parts related to the fracture process. Efficient filter techniques are necessary to enhance the signal-to-noise ratio in acoustic emission analysis. In comparison to conventional Fourier transform based filter techniques there are advantages of wavelet based techniques. Transforming signals to the wavelet domain the time information included in the signals phase is conserved. This enables new ways of signal analysis and conditioning [GROSSE, RUCK ET AL. 2001; GROSSE ET AL. 2002]. An example of a successful filtering is shown in Fig. 1.

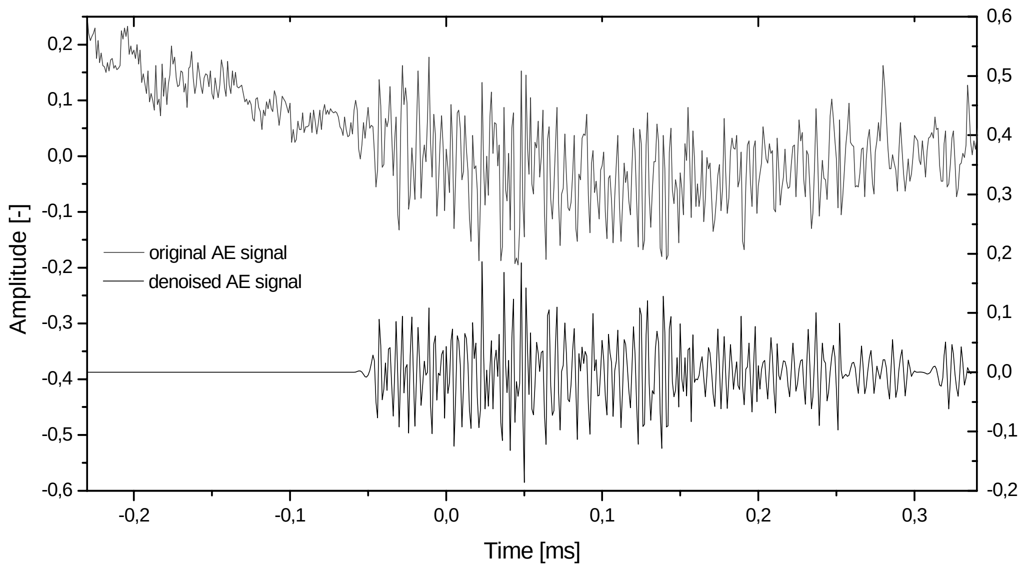

Fig. 1: Original (upper) AE signal and denoised (lower) AE signal using the wavelet algorithm WaveFilter [GROSSE ET AL. 2002]. *Both signals are shifted concerning the amplitude axis for better comparizion. Note that the left axis scale is valid for the upper and right axis for the lower signal.*

Quantitative analysis techniques

Fracture processes of seismic events are represented by the moment tensor. This tensor describes equivalent acting forces of a point source. Meanwhile, there are different *moment tensor inversion* (MTI) methods applied on AE data as well. Typical inversion methods are based either on a synthetic material model created by the user to represent the wave propagation in the medium [OHTSU 1991] or on finite difference methods [FUKUNAGA & KISHI 1986; ENOKI & KISHI 1988], which can take the heterogeneity of materials into account. The influence of sensor characteristics, such as angle dependent sensitivity, is usually evident. Methods based on a combination of these techniques [LANDIS & SHAH 1995] are often not sufficient due the attenuation of the material. The significance of the Green's functions, which describe the influence of the medium along the travel path, is obvious. The Green's functions also account for the characteristics and the coupling of the sensors. As long as these influences can be eliminated, MTI can be applied directly. To solve the set of equations, data from at least six sensors are required [GROSSE & REINHARDT ET AL. 1997; GROSSE 2004].

A relative approach is usually better suited to the problem, since the material model is extracted directly from the data, if it is not eliminated all together. Relative methods, on the other hand, are only applicable if some acoustic emissions are recorded during the experiment under certain assumptions of the source locations. The distance between the hypocenters (AE focuses) of all AE events should be small compared to the travel path from the event to the sensors. If this is the case the reliability of the results increases with the number of events due to the reduction of statistical noise in the data.

A method developed by DAHM [1993; 1996], called *relative moment tensor inversion* (RMTI), is based on the elimination of the elementary seismograms in the equations and allows one to invert directly to the moment tensor without determining the Green's functions in advance. Practice shows [GROSSE, WEILER ET AL. 1997] that up to hundreds of acoustic emissions are often recorded. Usually, they are clustered in well-defined regions; a presupposition to apply RMTI. The travel path from different events in a cluster to a single sensor is approximately the same (Fig. 2) and thus the dynamic part of the Green's functions can be eliminated.

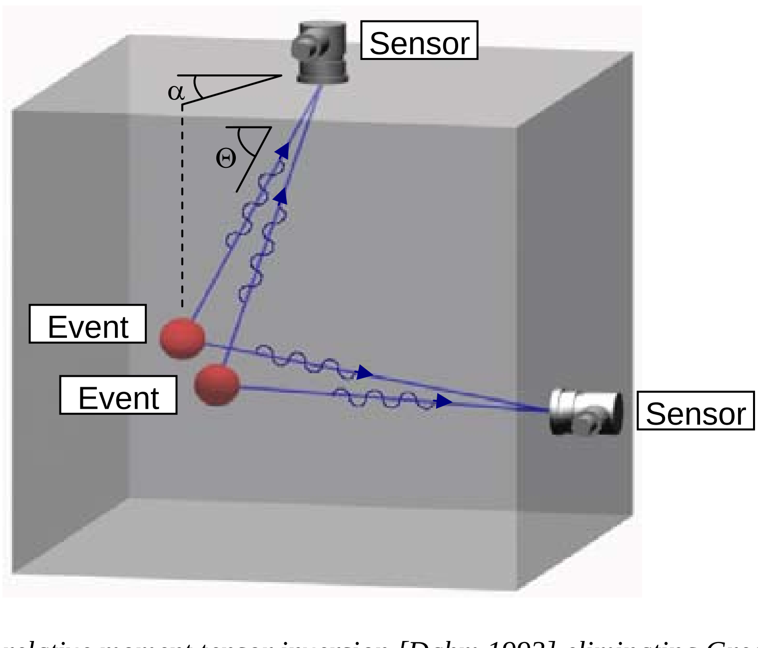

Fig. 2: Principle of the relative moment tensor inversion [Dahm 1993] eliminating Green's functions for events with almost the same travel path; Θ = incidence angle; α = azimuth.

A more detailed description of the theoretical background of MTI and RMTI can be obtained in the literature [OHTSU ET AL. 1998; GROSSE 1999; GROSSE & REINHARDT ET AL. 2003; GROSSE 2004]. Hybrid MTI methods [ANDERSON 2001] were tested also and the results are published in FINCK ET AL. [2003].

Signal classification using magnitude squared coherence functions

Acoustic emission data often comes from a similar source like a growing crack. Recording AE signals during the failure of a structure, this fact is expressed by numerous clusters occurring during the recording interval as described in the previous section. A cluster is defined as a location with a certain extension in the specimen, where more than two events are located close to each other in relation to the travel path and considering the uncertainties of localization. Since it is not practicable to investigate all events in a cluster in the way, described in the previous chapter, it is more efficient to look for similar events.

The assumption can be verified that apart from the influence of the medium along the travel path and of the different transducer characteristics, similar source mechanisms result in acoustic emission signals in such a cluster of similar shape, i.e. similar frequency characteristics. The similarity of two signals can be quantified using a mathematical tool called *magnitude squared coherence* (MSC) [CARTER & FERRIE 1979; GROSSE 1996; KÖPPEL 2002]. A software called *SiSima-MSC* [BAHR & GROSSE 2003] calculating the signal similarities basing on the MSC sum method can do this job automatically.
With a transformation of the signals into the frequency domain and the calculation of coherence functions, it is possible to find a quantitative relationship between the waveforms of signals with similar source mechanisms. This method is intended to be used for rapid, systematic classification of the signals to recognize similarities and differences in signal pattern.
However, it has to be stated that the signal form of different events in AET is often not ruled by the fracture process alone. Especially for large structures it is true that the signal is influenced after a few oscillations by side reflections or other effects related to the material (anisotropy, heterogeneity, etc.), the propagation path or the sensor characteristics (sensor resonance, coupling, etc.) than by the source [KÖPPEL 2002]. Therefore, the described correlation technique is beneficial for small structures mainly.

3. Application to large structures

Damage and failure processes often generate several thousand events from one damage zone within a very short time, revealing a huge amount of data. With parameter-based acoustic emission technique a fast but only rudimentary analysis can be performed often on-line. As stated above, only signal-based acoustic emission analysis permits detailed investigations on fracture mechanics and failure processes. Analysing the data by hand is a very time consuming process. Therefore, the development of automatic analysis methods, including data conversion, denoising, and localization by the use of an automatic onset determination, moment tensor inversion and other features like b-value determination or the use of magnitude-squared coherence functions, is indispensable.

The use of fast recorders and processing software is one requirement for applications insitu using signal-based AE techniques. Another point maybe even more important is the development of cheap but reliable sensor techniques. Due to the attenuation of acoustic waves (geometrical spreading) in concrete structures numerous sensors have to be applied to cover all critical parts. On the other hand a wired connection between all sensors and the processing facility is increasing the installation expenses in an inefficient way.

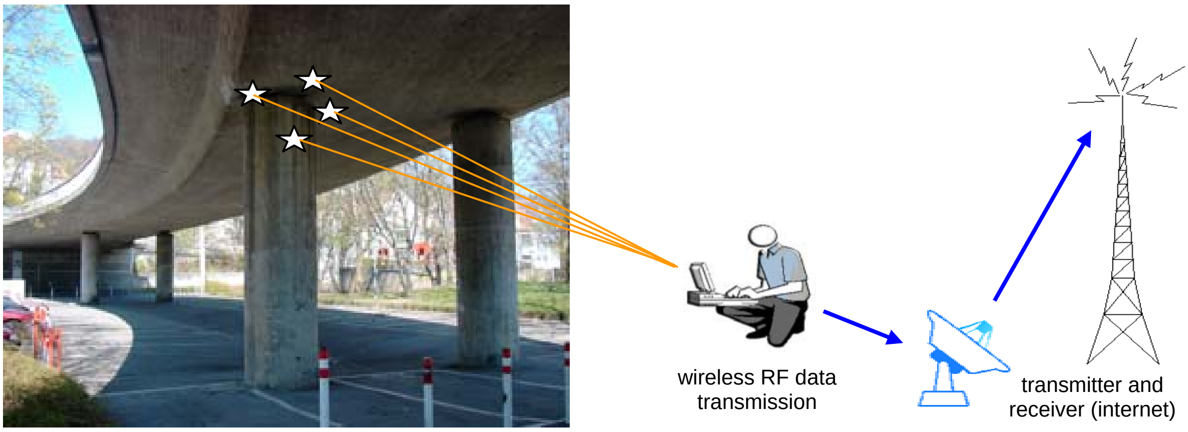

Fig. 3: Diagram of wireless sensing of large structures using radio frequency transmission technique.

Therefore, the objective must be to develop a prototype of innovative, reliable hard- and software technologies for the continuous monitoring of structures like bridges (Fig. 3) using wireless sensors. Tiny self-contained sensor systems (called "Motes" or "smart dust") are installed near critical structural points in a key building - the damage occurs locally, but effects globally. Sensors report the location and kinematics of damage during or after an extreme event, allowing rapid, accurate structural health determination. Public safety is assured as unseen structural damage is identified without costly and dangerous deconstruction. Onboard intelligence discerns normal structural deterioration and meaningful damage. The traditional recording methods on the other hand (like fibre optic Bragg grating sensor system for strain measurement on large structures) send back too much data to traditional servers instead of information.

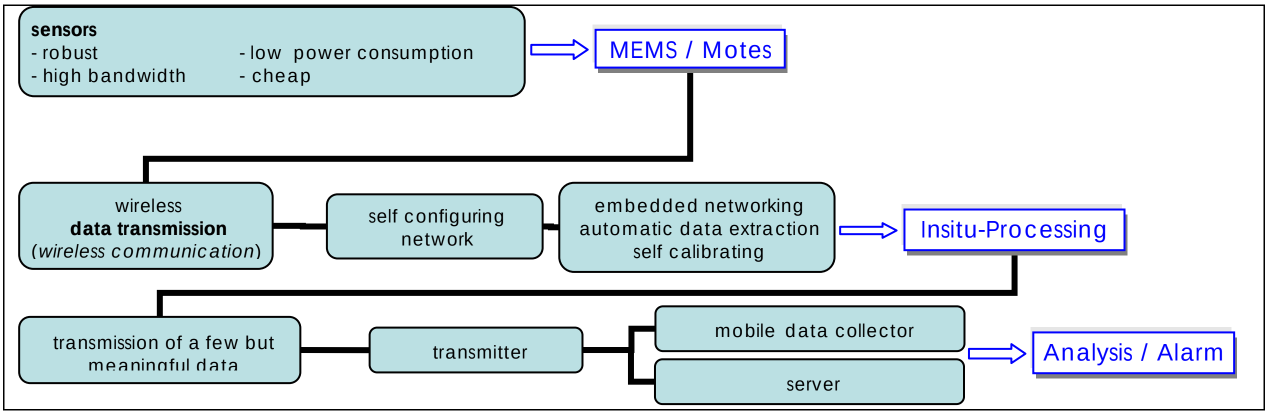

Fig. 4: Scheme of data processing and transmission for the remote monitoring of structures.

The self-assembled networks examine structural response amongst their topologies, identifying an optimum system characterization of the local structural state. The ideas behind are:

- The computation is much more energy efficient than data transmission
- To send back a few poles rather than terabytes of raw data is more efficient
- Intelligent algorithms allow the computational burden to be shared amongst local processors
- A detailed constitutive model of the structure can be initialized with the installation of sensor webs
- The model can be continuously updated by the constant feedback of local state
- The model instructs the Mote assemblage to re-configure in order to vary characterization granularity (self-scaling)

Fig. 5: Example of existing MEMS and „Motes“(courtesy of UC Berkeley).

First steps of the development are:

- Creation of embedded network systems to sort out the data and to establish processing and analysis tools.
- Application analysis and adaptation for different bridges types
- Interaction with simulation techniques to identify and classify typical damages and to define the criticality of recorded damages. Interaction with other non-destructive testing methods to classify the damage by other non-destructive testing methods
- Test of algorithms under laboratory conditions
- Test at existing and new bridge structures, adjustment of algorithms and mechanical parts and development of robust, cost-effective systems

Installing such new and cost effective wireless AE system a monitoring of existing and new concrete bridges as well as existing and new steel bridges is possible without having any traffic-free time. A monitoring system for large structures will be developed in cooperation between different institutions in the USA and Germany basing on a new kind of sensors using MEMS techniques. Micro-Electro-Mechanical-Systems (MEMS) are the first choice if there is a need for cheap, robust, small and wireless sensors. Sensors with a target price of less than some 10 € are essential for monitoring systems to be accepted by the industry. Implemented wireless communication techniques will reduce the application and maintenance costs significantly.
These sensors should be intelligent, self-networking, asynchronous, wireless, adaptive, dynamically reprogrammable, cheap and small. First sensor prototypes along with adaptive self configuring wireless systems meeting most of these requirements will be tested during summer 2004 at structures in California and Germany. While such a system is scalable and adjustable to different type of bridges it is expected that the acceptance of such a system is high at least for structures of higher value or with critical defects. The described technique will work as a maintenance free monitoring system sending data (alarm data) via intranet to a data centre or alarm messages per SMS automatically to the monitoring engineer.

4. Summary and outlook

The described methods enable techniques which are a valuable tool for the analysis of fatigue and failure in materials. Some of the advantages are the possibility of continuous monitoring of damage growth in non-transparent materials and the determination of fracture type, size and orientation using moment tensor inversion techniques.
In comparison to conventional Fourier transform based filter techniques the advantages of wavelet based techniques were described. Transforming signals to the wavelet domain the time information included in the signals phase is conserved. This enables new ways of signal analysis and conditioning. One application is the design of sophisticated wavelet filters to enhance the signal-to-noise ratio in acoustic emission analysis.

Further on, examples of signal-based AE techniques were given including similarity analysis, moment tensor inversion and fracture type classification. Since these techniques are time consuming automization is necessary to deal with large amount of AE data. Together with recently developed transient-recorder based AE equipment new data processing techniques have been developed.

For the future development of the presented techniques in laboratory several approaches will be tested including new broadband sensors [GLASER ET AL. 1998] on the hardware side and different analysis techniques like hybrid MTI methods [ANDERSEN 2001] and b-value analysis techniques. There is a large potential of applications including monitoring techniques of large structures like Bridges [GLASER 2003].

Acknowledgement

Most of the described results were obtained in the frame of two collaborative projects, Sonderforschungsbereich SFB381, funded by the Deutsche Forschungsgemeinschaft DFG, and project “Sustainable Bridges”, funded by the European Community. Illustration describing applications of MEMS to structures in civil engineering were provided by Prof. Steven D. Glaser from the University of California in Berkeley. His support is gratefully acknowledged.

References

Andersen, L. M.: *A relative moment tensor inversion technique applied to seismicity induced by mining*. PhD thesis, University of the Witwatersrand, Johannesburg (2001), 201 pp.

Bahr, G., Grosse, C. U.: *SiSima-MSC – Calculation of signal similarities using the magnitude squared coherence.* SiSima-MSC Manual, vers. 1.2., University of Stuttgart, Institute of Construction Materials (2003).

Carter, G. C., Ferrie, J. F.: *A coherence spectral estimation program*. Weinstein, C. J. (Programs for digital signal processing), 2.3-1-2.3-18. 1979. IEEE Press.

Dahm, T.: *Relative moment tensor inversion based on ray theory: theory and synthetic tests*. Geophys. J. Int. 124 (1996), 245-257.

Dahm, T.: *Relativmethoden zur Bestimmung der Abstrahlcharakteristik von seismischen Quellen*. PhD Thesis, University of Karlsruhe, Germany, 122 p (1993).

Enoki, M., Kishi, T.: *Theory and analysis of deformation moment tensor due to microcracking*. Int. J. Frac. 38 (1988), 295-310.

Finck, F., Yamanouchi, M., Reinhardt, H.-W., Grosse, C. U.: *Evaluation of mode I failure of concrete in a splitting test using acoustic emission technique*. Intern. J. of Fracture 124 (2003), 139-152.

Fukunaga, Y., Kishi, T.: *Progress in Acoustic Emission III*. Yamaguchi,K. & et al. (Eds.), Jap. Soc. of Non-Destr. Insp., Tokyo (1986), 722-731.

Fourier, J.: *1822 - The Analytical Theory of Heat.* London, Cambridge Univ. Press, 1878.

Gabor, D.: *Theory of Communication*. J. Inst. Electr. Eng. 93, London, III (1991), 891-906.

Geiger, L.: *Herdbestimmung bei Erdbeben aus den Ankunftszeiten*. Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen 4 (1910), 331-349.

Glaser, S. D., Weiss, G. G., Johnson, L. R. *Body waves recorded inside an elastic half-space by an embedded, wideband velocity sensor*. L. Ac. Soc. Am. 104 (3), Pt. 1 (1998), 1404-1412.

Glaser, S. D.: *New sensor technologies for civil engineering.* <http://ce.berkeley.edu/~glaser/>, Personal communication (2003).

Grosse, C. U., Weiler, B., Reinhardt, H. W.: *Relative moment tensor inversion applied to concrete fracture tests*. J. of Acoustic Em. 14, (1997), no. 3-4, S64-S87.

Grosse, C. U., Reinhardt, H. W., Dahm, T.: *Localization and Classification of Fracture Types in Concrete with Quantitative Acoustic Emission Measurement Techniques*. NDT&E Intern. 30, (1997), no. 4, 223-230.

Grosse, C. U., Reinhardt, H. W.: *Entwicklung eines Algorithmus zur automatischen Lokalisierung von Schallemissionsquellen*. Material testing 41 (1999), 342-347.

Grosse, C. U.: *Grundlagen der Inversion des Momententensors zur Analyse von Schallemissionsquellen*. In: "*Werkstoffe und Werkstoffprüfung*", Festschrift zum 60. Geb. von Prof. Reinhardt (C. Grosse, ed.), Libri BOD (1999), 82-105.

Grosse, C. U.: *Quantitative zerstörungsfreie Prüfung von Baustoffen mittels Schallemissionsanalyse und Ultraschall*. PhD Thesis, University of Stuttgart, Germany, 168 p (1996).

Grosse, C. U., Ruck, H. J., Bahr, G.: *Analyse von Schallemissionssignalen unter Verwendung der Wavelettransformation,* 13. Kolloquium AE DGZfP Report 78 (2001), 41-50.

Grosse, C. U., Motz, M., Reinhardt, H. W., Kröplin, B.: *Signal conditioning algorithms in acoustic emission analysis using wavelets.* NDT.net 7 (2002), no. 9.

Grosse, C. U., Reinhardt, H. W., Finck, F.: *Signal-based acoustic emission techniques in civil engineering*. J. Mat. Civ. Eng. 15 (2003), no. 3, 274-279.

Grosse, C. U.: *Akustische Verfahren zur zerstörungsfreien Prüfung von Baustoffen und Bauteilen.* Habilitationsschrift, Universität Stuttgart (2004), 131 p. (in print)

Grosse, C. U., Finck, F., Kurz, J., Reinhardt, H. W: *Improvements of the acoustic emission technique using wavelet algorithms, coherence functions and automatic data analysis techniques*. J. of Construction and Building Mat. 18 (2004), No. 3, 203-213.

Hudson, J. A., Pearce, R. G., Rogers, R. M.: *Source type plot for inversion of the moment tensor*. JGR 94 (1989), no. B1, 765-774.

Köppel, S.: *Schallemissionsanalyse zur Untersuchung von Stahlbetontragwerken*. PhD Thesis ETH No. 14490, Swiss Federal Institute of Technology (ETH) Zürich, Switzerland, 172 p (2002).

Köppel, S., Grosse, C. U.: *Advanced acoustic emission techniques for failure analysis in concrete*. Proc. of 15th World Conf. on NDT, Rome, on CD-ROM (2000).

Köppel, S., Vogel, T.: *Localization and identification of cracking mechanisms in reinforced concrete using acoustic emission analysis*. Proc. 4. Int. Conf. on Bridge Management, Surrey (2000), 88-95.

Knopoff, L., Randall, M. J.: *The compensated linear-vector dipole: A possible mechanism for deep earthquakes*. JGR 75 (1970), no.26, 4957-4963.

Landis, E. N., Ouyang, C. & Shah, S. P.: *Automated Determination of First P-Wave Arrival and Acoustic Emission Source Location.* J. of Acoustic Em. 10 (1-2), S97-S103. (1992).

Landis, E. N.: *A quantitative acoustic emission investigation of microfractures in cement based materials.* Thesis, Northwestern University, Evanston, USA, 185 p (1993).

Landis, E., Shah S. P.: *Signal analysis for quantitative acoustic emission testing.* Nondestructive Testing Methods; ASCE; New York (1995), 45-56.

Ohtsu, M., Okamoto, T., Yuyama, S.: *Moment tensor analysis of acoustic emission for cracking mechanisms in concrete*. ACI Structural Journal 95 (1998), no. 2, 87-95.

Ohtsu, M.: *Simplified Moment Tensor Analysis and Unified Decomposition of Acoustic Emission Source: Application to in-Situ Hydrofracturing Test*. JGR 96 (1991), 6211-6221.

Ohtsu, M., Shigeishi, M., Iwase, H., Koyanagi, W.: *Determination of crack location, type and orientation in concrete structures by acoustic emission*. Mag.Conc.Res. **155**, 127-134 (1991).

Oncescu, L. & Grosse, C. U.: *HYPO^{AE}* **-** *A program for the localization of hypocenters of acoustic emissions.* Computer Program, Rev.2.1, (1998).

Zang, A., Wagner, F. C., Stanchits, S., Dresen, G., Andresen R., Haidekker M. A.: *Source Analysis of Acoustic Emissions in Granite Cores under Symmetric and Asymmetric Compressive Load*. Geophys. J. Int. 135 (1998), 1113-1130.