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Identifying Acoustic Emission Events with Similar Transfer Functions

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Abstract

A special similarity measurement for acoustic emission events based on sampled signals from multiple channels was developed. Data from pairs of channels is processed in a way that events with different source functions, but the same source mechanism and transfer functions show large correlation.

The evaluated X22-correlation can be used for clustering and sub-clustering. Additionally, a double time difference is evaluated, which can be used for double difference location [1] also called relative location [2]. An additional application of this similarity measurement is the comparison of measured signals to the ones calculated by simulations.

Introduction

There are a lot of methods for the evaluation of AE data [3], and clustering of events an important task. Techniques which are applied in seismology [2, 4] are also interesting for the evaluation of AE-data, but one has to consider that dispersive plate waves are important in AE.

Here a similarity measurement based on sampled signal data, which can be used for clustering, but also for relative location processing, as used in seismology, was developed.

Mathematical model

The model (Fig. 1) consists of a body with a number of acoustic emission (seismic) sensors (SEN_j) mounted at fixed positions. Transient acoustic emission signals from micro fracture or other natural sources (E_i) are acquired by the acoustic emission equipment via sensors, preamplifiers, and filters.

The wave initiation, wave propagation, and the measurement of the surface movement are mathematically described as following:

$$a_{ij} = s_i(t) * u_{ij}(t) * e_j(t) \qquad (1)$$

$s_i(t)$	source function for the event E_i
$u_{ij}(t)$	transfer function from the source function $s_i(t)$ to the sensor SEN_j
$e_j(t)$	transfer function of sensor (SEN_j), amplifiers, filters and acquisition equipment
$a_{ij}(t)$	signal function at sensor SEN_j from event E_i
*	convolution operator

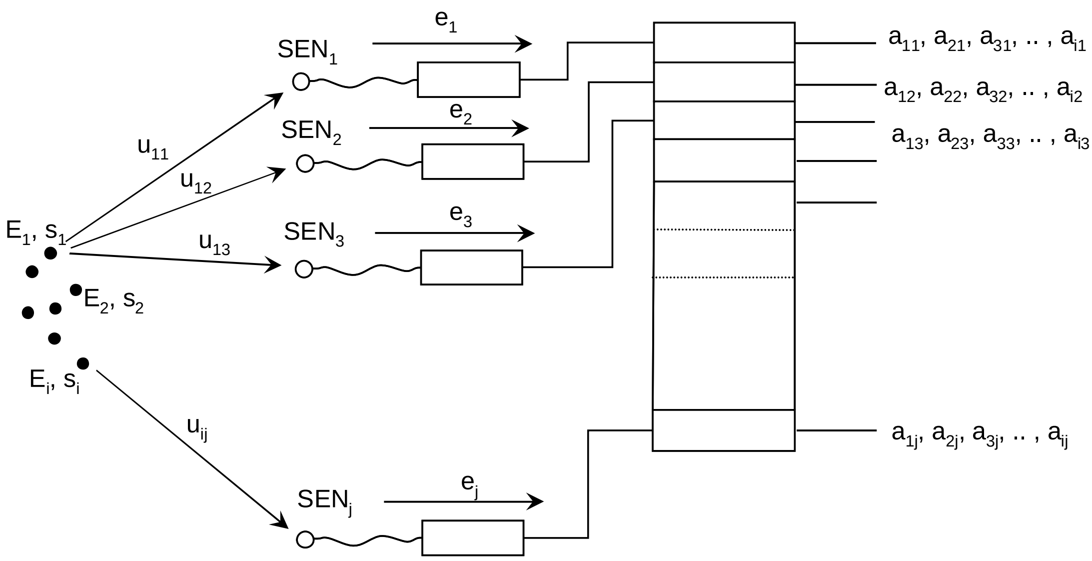

Fig. 1. Basic model for wave transfer

The model is based on the following assumptions:

- Acquired signal data a_{ij} can be separated in a way that every a_{ij} is caused by one single event. This means that the time difference between events E_i must be large enough that signals from different events do not overlap.
- The signals a_{ij} acquired at different sensors SEN_j caused by one event E_i can be grouped.
- The signals a_{ij} acquired at different sensors SEN_j caused by one event E_i have a common source function $s_i(t)$.
- The relation of the source function $s_i(t)$ to the acquired signals can be described by linear differential equation and can, therefore, be described by convolution with transfer functions ($u_{ij}(t) * e_j(t)$).

Events with similar transfer functions

Now a pair of events (E_1 and E_2) and the measured signals from these events at two sensors (SEN_1 and SEN_2) are investigated (Figure 2).

Now we search for a check to find out whether or not the transfer functions to the considered sensors (u_{1j} and u_{2j}) are (almost) the same for the considered two events - The source functions may be different. Such a similarity is expected if the source orientation and mechanism of both events is the same, and the events are located near from one another ($\vec{x}_2 = \vec{x}_1 + d\vec{x}_{12}$).To allow for local shifts dx_{12}, differences in the time delays $dt_{1-2,1}$ and $dt_{1-2,2}$ should not destroy the similarity:

$$u_{21}(t) \approx u_{11}(t - dt_{1-2,1}) \quad (2)$$

$$u_{22}(t) \approx u_{12}(t - dt_{1-2,2}) \quad (3)$$

The time difference $dt_{1-2,1}$ is the difference of the delays in the transfer functions from the two source functions to the first sensor and $dt_{1-2,2}$ is the same difference to the second sensor.

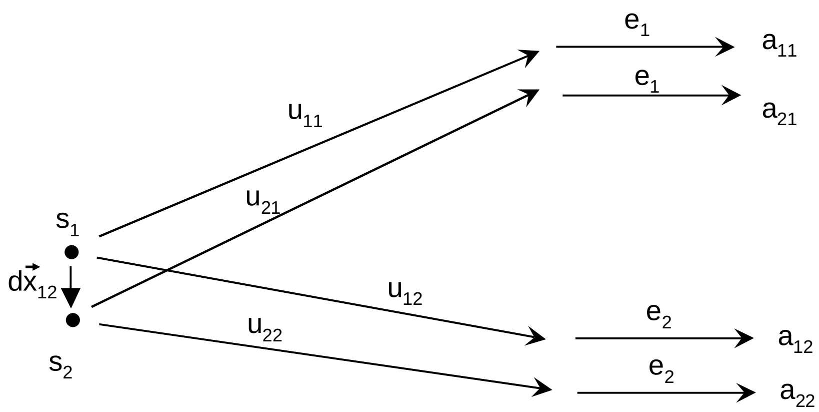

Fig. 2. Two similar events

In acoustic emission measurements only the acquired signals a_{ij}, not the source functions, are available for checking similarity. Using the signals from one sensor only does not allow to "cancel" the source function. Ratios of the acquired signals at one channel to the one at another channel seam to be promising, because in a fraction the parts which are the same for the nominator and the denominator are cancelled. The problem with fractions is that here instead of division, deconvolution operation had to be used, which is impracticable. Therefore, another approach, based on convolutions of signal functions, is chosen:

$$(a_{22} * a_{11})(t) \approx (a_{12} * a_{21})(t - dt_{1-2,1-2}) \quad (4)$$

In this equation * is convolution and $(t - dt_{1-2,1-2})$ at the right side means that the function resulting from convolution $(a_{12} * a_{21})$ is delayed by a time $dt_{1-2,1-2}$.

(Eq. 4) is fulfilled if (Eq. 2) and (Eq. 3) and a view simple conditions are fulfilled. To show these conditions, the model for the wave transfer given in (Eq. 1) is inserted in (Eq. 4):

$$(s_2 * u_{22} * e_2 \ * s_1 * u_{11} * e_1)(t) \approx (s_1 * u_{12} * e_2 * s_2 * u_{21} * e_1)(t - dt_{1-2,1-2}) \quad (5)$$

$$((u_{22} * u_{11}) * (s_1 * s_2) * (e_1 * e_2))(t) \approx ((u_{12} * u_{21}) * (s_1 * s_2) * (e_2 * e_1))(t - dt_{1-2,1-2}) \quad (6)$$

Reordering of (Eq. 5) leads to (Eq. 6), where we can see the following:

The convolution $(s_1 * s_2)$ arises on both sides so that the similarity even holds for different source functions s_1 and s_2. The important condition is that the signals acquired from one event at different sensors have a common source function.

The transfer functions of sensor and acquisition equipment arise also on both sides. If the same sensors and equipment are used for both events, sensor and equipment transfer functions of the two channels may be different without destroying similarity in (Eq. 4).

Another case, which is not covered by the notation used here, may be usefully when measured signal data has to be compared to simulated ones: If channels 1 and 2 have the same transfer function $e_1 = e_2$ (equivalent sensors, filters, and equipments), different transfer functions could be used for event 1 event 2. The data a_{11} and a_{12} (event 1) could be a measured measurement signal and a_{21} and a_{22} (event 2) a calculated surface movement.

Quantification of similarity (X22-correlation)

When applying (Eq. 4), the left and the right hand sides are never exactly equal. Therefore, a quantitative measurement of similarity is necessary. In this investigation the largest success was reached by taking the maximum of a normalized cross correlation function.

Therefore, the sampled signals $a_{ij}{}^{k}$ (k indicating sampled signals) are used, and the left and the right sides of (Eq. 4) were evaluated:

$$c_{2211}{}^{k} = a_{22}{}^{k} * a_{11}{}^{k} \quad (7)$$

$$c_{1221}{}^{k} = a_{12}{}^{k} * a_{21}{}^{k} \quad (8)$$

The normalized cross-correlation function is evaluated in the following way:

$$r_{n,c,1-2,1-2}(\Delta k) = \frac{\sum_{k\in K} c_{1221}{}^{k}(k)\cdot c_{2211}{}^{k}(k+\Delta k)}{\sqrt{\sum_{k\in K} c_{1221}{}^{k}(k)^2 \cdot \sum_{k\in K} c_{2211}{}^{k}(k+\Delta k)^2}} \quad (9)$$

For the normalisation in (Eq.9), it is assumed that the mean values of the convolution functions $c_{2211}{}^{k}$ and $c_{1221}{}^{k}$ are zero. The set K of integers, for which the sums are evaluated, has to include the beginning of the transient signal. If the whole time window with nonzero signal caused by the corresponding event is acquired and usable, Eq. 7 to 9 can easily be evaluated in the frequency space. If this is not the case (which was the case for the data used in this paper), for each specific Δk, the set K must be the same for the nominator as for the dominator. For incomplete signals, consistent evaluation of the equations was done in time space. This time consuming option was chosen here, being aware that further development is necessary to reduce calculation time.

The similarity is now quantified as the maximum of this normalized cross-correlation function:

$$\rho_{c,1-2,1-2} = \max_{\Delta k}\ (r_{n,c,1-2,1-2}(\Delta k)) \quad (10)$$

$$\Delta k_{1-2,1-2} = \arg\max_{\Delta k} (r_{n,c,1-2,1-2}(\Delta k)) \quad (11)$$

Because of the crosswise convolution of the signals from two events and two channels, this type of similarity measurement $\rho_{c,1-2,1-2}$ is called X22-correlation.

Additionally, the time shift for the maximum the cross-correlation function $\Delta k_{1-2,1-2}$, which corresponds to the double time difference $dt_{1-2,k-l}$, is evaluated. This double time difference can be used for double difference location calculations [1], also called relative location [2].

Simple cross-correlation between measured signals $\rho_{a,1-2,1}$

A simpler way of comparing the signals from different events is to build the maximum of the normalized cross-correlation function (Eq. 9-11) directly for the signals acquired at one channel j (a_{1j} and a_{2j}) instead of applying it on the convolutions $c_{2211}{}^{k}$ and $c_{1221}{}^{k}$. In this way one gets a similarity measurement for each channel (instead of each channel combination). In this way differential travel times for earthquake earthquake relocation are sometimes evaluated [5]. The maxima of these normalized cross-correlation functions are called simple correlation $\rho_{a,1-2,1}$ and used for comparison in this paper.

Applying the similarity measurement on different artificial sources

For testing the introduced similarity measurements, artificial sources with equal direction of stimulation force were applied on a simple rectangular steel plate (Figure 3a). Four resonant AE-sensors (VE150[1]) with a resonant frequency of 150 kHz were applied on the plate and connected to a AMSY5[1] equipment.

For the first two artificial source types (Table 1), a VE150 sensor was electrically stimulated by two different signal forms. Additionally, pencil lead breaks of 0.3 mm and hardness 2H were used directly and via a centre punch (Figure 3b).

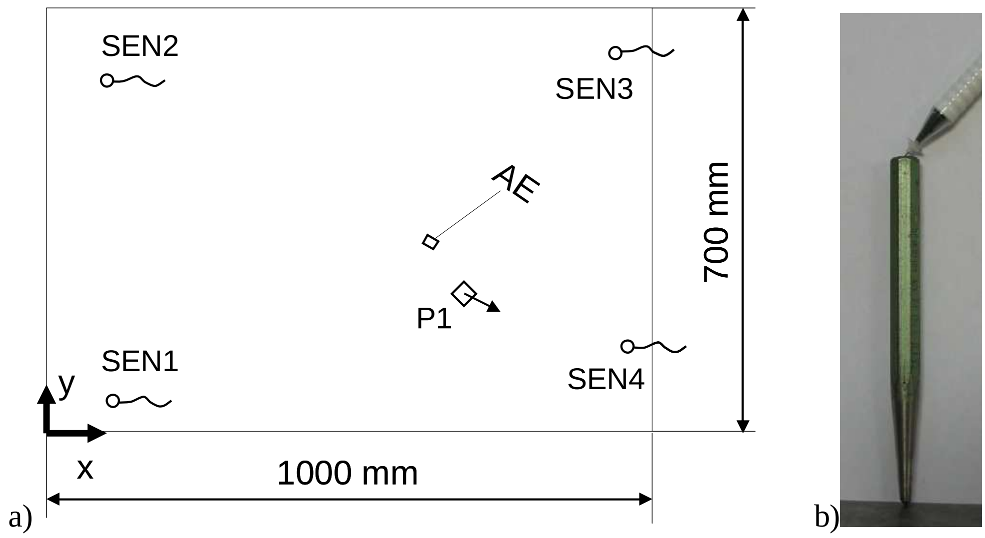

Figure 3: a) Arrangement for simple tests; steel plate with thickness of 6 mm; b) Pencil lead break via centre punch

In a first step, all the artificial sources were applied in point P1 (Figure 3a). The signals were acquired with a sample frequency of 5 MHz, and 2056 samples were used (Figure 4).

Selected X22-correlations and simple cross-correlations are shown in (Table 2). Here the X22-correlations ($\rho_{c,1-2,k-l}$) are given for all sensor combinations. At the left side mean values ($\overline{\rho}_{c,1-2}$) are given. In the line below the evaluated double time differences ($dt_{1-2,k-l}$ corresponding to $\Delta k_{1-2,1-2}$) are listed. For comparison simple cross-correlations ($\rho_{a,1-2,k}$), are given for each sensor.

Because in the case of the pulsar, a common source function for each event exists, perfect X22-correlation is shown for different electrical sources at the same pulsar. Also large X22-correlation was found for the other combinations of source types. The X22-correlation of PU1 vs. PL1 at sensor combination 1-3 shows a double time difference $dt_{1-2,k-l}$ which is not valid, indicating that a check of the evaluated time differences is necessary.

[1] Vallen Inc.

Table 1: Tested event types

	Description
PU1	Piezoelectric transducer VE150 with broad band type voltage pulse (Vallen internal pulser)
PU2	Piezoelectric trans. VE150 with 110 kHz small band type voltage pulse (function generator- sin-function windowed by a sin-function with 10 oscillations)
PL1	0,3 mm pencil lead break hardness H2 on surface
PLK	0,3 mm pencil lead break hardness H2 via a centre punch

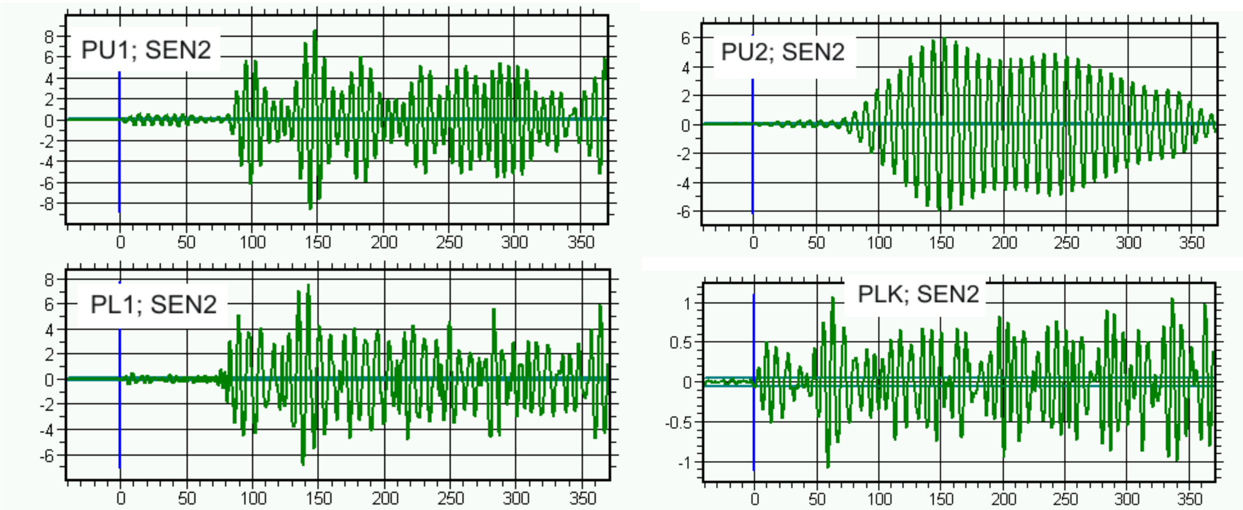

Fig. 4. Signals (voltage in [mV] vs. time in [µs]) of tested event types at sensor 2

The simple cross-correlations ($\rho_{a,1-2,k}$) are small in these cases because events with different source functions are compared.

The mean values of these correlations are summarized in (Table 3). Here also correlations of the same type of source (repeated experiment) are given. Additionally, one source 70 mm from P1 is included. The simple cross-correlation shows only large values (>0.9) if source location and source type are the same. For different source types or larger distances the values are between 0.2 and 0.5 (0.59). In the case of X22-correlation large values are seen also if the source functions are different. Sources with larger distances (different transfer function) from one another have X22-correlations from 0.6 to 0.83.

Dependence of the similarity measurement on the distance between sources

For relative location processing based on the evaluated double time differences, it is important to know the behaviour of the X22-correlation if small distances arise between the sources. Therefore, some pencil lead breaks were performed in different distances from P1 (direction to Sensor 4 - Figure 3a). In Table 4 the X22-correlations between sensors 2 and 4 were listed, showing high values and appropriate double time differences up to a distance of 5 mm. This corresponds to a double difference in the propagation distances of 10 mm.

Table 2: X22-correlation for different combinations of selected event types at point P1

		Sensor combination k-l						Mean value	Symbol mean
		1-2	1-3	1-4	2-3	2-4	3-4		
PU1 vs. PU2	$\rho_{c,1-2,k-l}$	0.999	0.997	0.997	0.9995	0.9993	0.9992	0.999	$\overline{\rho}_{c,1-2}$
	$dt_{1-2,k-l}$ [µs]	0	0	0	0.2	0.2	0		
	$\rho_{a,1-2,k}$	SEN1: 0.30; SEN2: 0.24; SEN3: 0.13; SEN4: 0.18						0.21	$\overline{\rho}_{a,1-2}$
PU1 vs. PL1	$\rho_{c,1-2,k-l}$	0.98	0.94	0.97	0.82	0.86	0.97	0.92	$\overline{\rho}_{c,1-2}$
	$dt_{1-2,k-l}$ [µs]	0	~~-6.4~~	0.6	0.8	0.8	-0.2		
	$\rho_{a,1-2,k}$	SEN1: 0.74; SEN2: 0.65; SEN3: 0.61; SEN4: 0.68						0.67	$\overline{\rho}_{a,1-2}$
PL1 vs. PLK	$\rho_{c,1-2,k-l}$	0.98	0.97	0.95	0.95	0.98	0.97	0.97	$\overline{\rho}_{c,1-2}$
	$dt_{1-2,k-l}$ [µs]	-0.2	-0.4	-0.4	-0.6	-0.6	0.2		
	$\rho_{a,1-2,k}$	SEN1: 0.64; SEN2: 0.60; SEN3: 0.56; SEN4: 0.54						0.59	$\overline{\rho}_{a,1-2}$

Table 3: Summery of mean values X22-correlations and simple cross-correlations for different event types at point P1 and 70 mm from this point

$\overline{\rho}_{c,1-2}$ $\overline{\rho}_{a,1-2}$	PU1	PU2	PL1	PLK	PL1 – 70mm
PU1		0.999 0.21	0.92 0.67	0.95 0.44	0.64 0.34
PU2			0.99 0.52	0.995 0.51	0.83 0.43
PL1			0.99; 0.97 0.88; 0.96	0.97 0.59	0.58 0.45
PLK				0.995; 0.998 0.96; 0.992	0.69 0.38
PL1 – 70 mm					0.98 0.95

Table 4: X22-correlation for OP1 to different event types at different distances

		2 mm	5 mm	10 mm	15 mm
Window 1	$\rho_{c,1-j,2-4}$	0.99	0.92	0.76	0.73
	$dt_{1-j,2-4}$ [µs]	-2.0	-4.2	~~35~~	~~-5.2~~

Applying relative location with pencil lead breaks (double difference location)

Pencil lead breaks were performed on the plate to form the letters “AE” (Figures 3a and 5a). For the measured singals, X22-corrrelations and the corresponding double time differences were evaluated. Based on this data, a simple least square fitting algorithm, with the centre of the cluster as input value, was used for the evaluation of relative location. When using the signals from one event at each point no recognizable pattern was received. Extending the set by a second event at each point leads to a recognizable pattern (Figure 5b).

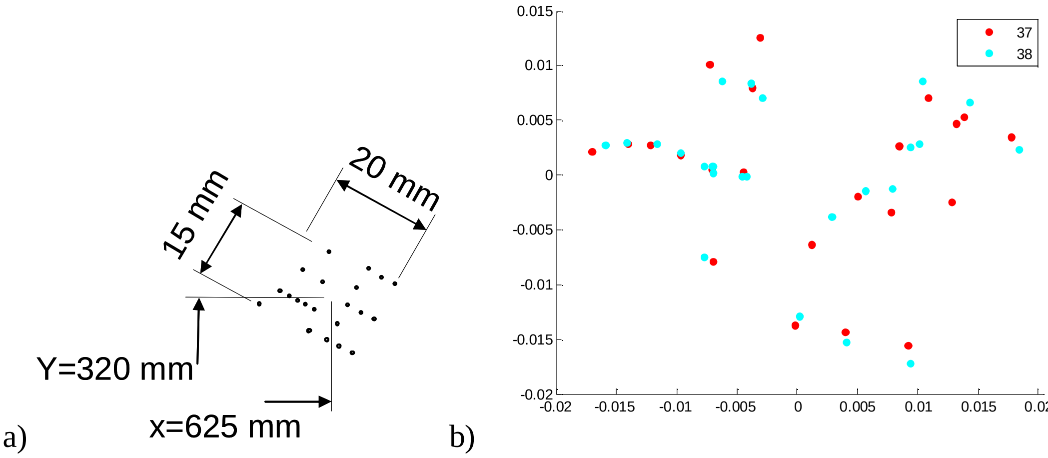

Figure 5: Relative Location of pencil lead breaks; a) pattern of pencil lead breaks; b) results from Relative Location processing

Conclusions

A similarity measurement called X22-correlation, which is able to group source according to there transfer function, was developed. With artificial sources, it could be shown that events at the same location and with the same direction of stimulation force, but with different source functions, show large X22-correlation.

This X22-correlation can be used for clustering and sub-clustering. The evaluated double time differences were used for double difference (relative) location processing.

At the moment, it is not known which type of source mechanism show this type similarity. For some applications, development is necessary to increase the maximum local distance between events for recognizing similarity. When large numbers of events have to be processed, development for decreasing computer load is necessary.

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