# Application of X22-Correlation to Some Types of Acoustic Emission Signals

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**Abstract.** In the last two EWGAE-meetings, X22-Correlation was presented, which compares acoustic emission events based on the measured signals at multiple sensors. By combining the signals measured at two sensors, X22-Correlation focuses on the difference between the radiation characteristics and the transfer-functions to the two sensors. The source functions and parts of the transfer functions which are the same for the considered sensors are cancelled by the algorithm.

The results of the algorithm are correlation values, which are a measurement of the similarity between two events, and double time differences. The similarity measurements can be used for clustering and the double time differences can be used for relative location processing.

Relative small X22-Correlations were evaluated for signals from a defect during a pressure test [3]. This is explained by the facts that facture events occurred at different locations and the characteristic of emission (direction) varied from one to the next fracture event.

Within this paper, X22-Correlation is applied to fracture signals from adhesive bonds. In the special case of a relative brittle failure at one side of the adhesive, large numbers of events were grouped together by X22-Clustering. This is plausible because similar fracture events are expected for this type of fracture.

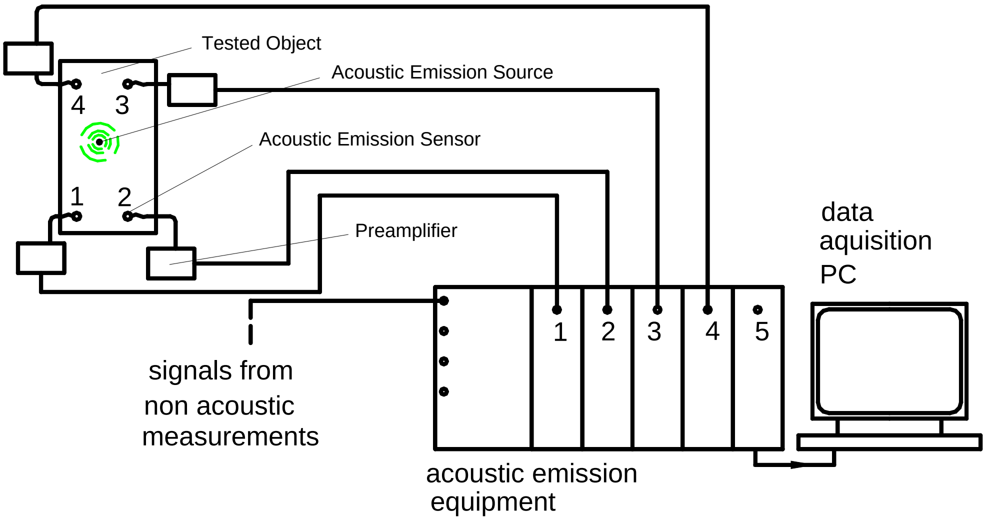
## Introduction

X22-Correlation is at a relatively early stage of development. Based on artificial signals, in [1, 2] it was shown that the algorithms works. In [3] the method was applied to acoustic emission signals from pressure tests.

The method is applied to data from classical multi-channel acoustic emission acquisition (Pic. 1). Sampled signals curves (transient recorder data) are used to compare acoustic emission events.

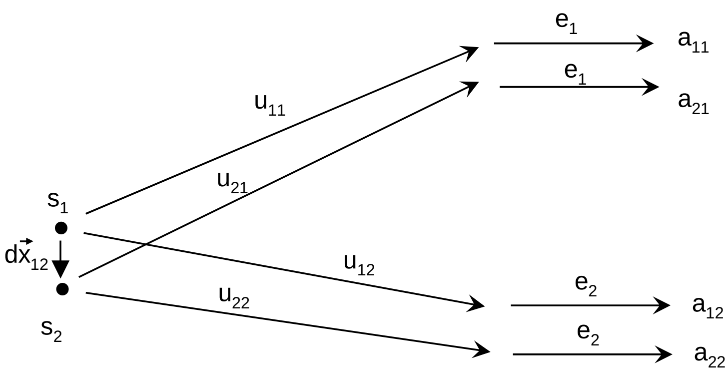
Correlation analysis can be used in different ways for analysing acoustic emission signals: To evaluate time differences for the location process of continuous signals, which is not considered in this paper, signals from different sensors are cross-correlated. In this paper always two events are compared and two types of correlation analysis called Direct Correlation (see 2.1) and X22-Correlation (see 2.2) are applied.

Triggered transient recorder signals of short duration are used. The analysis is based on the assumption that the signals have a defined beginning and end, and the whole signals are on the transient recorder pages. For the beginning of the signals, this assumption is sufficiently fulfilled. For the ending of the signals, this is failed frequently. One way of dealing with incomplete signals is to evaluate the correlations in time domain with a special method for normalisation of the cross-correlations [1, 2]. Another method is to apply damping before the analysis.




**Pic. 1.** General arrangement for acoustic emission measurement.

Usually transient recorder pages start some pre-triggering samples before a threshold crossing is detected. To get large cross-correlation, they must be synchronised by applying an appropriate time shift. To evaluate the optimal time shift, the cross-correlation function is evaluated and the maximum of this function is used. The corresponding time shift can be used for a special type of location processing, called relative location [1, 2].




**Pic. 2.** Transfer functions for two Events E1 and E2 with source functions $s_1$ and $s_2$ to two channels of acoustic emission equipment [1, 2].

$s_1$, $s_2$ source functions for the events $E_1$ and $E_2$

$u_{ij}(t)$ 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 acquired by the equipment from sensor $SEN_j$ and event $E_i$

### *2.1 Direct Correlation*

For the evaluation of the so called Direct Correlation (in [1, 2] called simple cross-correlation), cross-correlations are evaluated between signals from two events at the same channel. Using the notation of Pic. 2 means that cross-correlations are evaluated for signals $a_{11}$ with $a_{21}$ (channel 1) and for signals $a_{12}$ with $a_{22}$ (channel 2).

In multi-channel environments, Direct Correlation of two events is the mean value of the cross-correlations for the considered channels.

Interpretation: Large Direct Correlation means that the transient recorder curves are almost the same. This comparison identifies events with the same source and transfer functions. In situations with dispersive wave propagation, e.g. plate and shell structures, only events at the same (or almost the same) location show large Direct Correlation.

### *2.2 X22-Correlation*

The intension of X22-Correlation is to eliminate the source function and to compare the transfer functions only. The basic idea was to use deconvolution as a counterpart of division to eliminate the source function (Eq.1). By deconvolution of the signal of one channel with the signal from another channel, the source function, which is the same for both channels (same event), would be cancelled. Deconvoluted signals of different events would be compared e.g. be cross-correlation (Eq.1).

Because deconvolution is not convenient for comparing events (singularities), here the signals of two event at two channels are convoluted cross wise according to Eq.2, and equality is checked by cross-correlation. This procedure results also in a cancelation of the source functions and the result is called X22-Correlation. For more than two sensors, it can be evaluated for each sensor pair. Here the mean value is used in such cases.

$$a_{11}\ (*-1)\ a_{21} \approx a_{12}\ (*-1)\ a_{22} \qquad (1)$$

with (*-1) for deconvolution

$$a_{22} * a_{11} \approx a_{12} * a_{21} \qquad (2)$$

with * for convolution

Interpretation: Large X22-Correlation between two events is expected if the transfer functions and emission characteristics are the same. The source functions of the compared events may be different. One method to show that the method works is to use a piezoelectric pulser [1, 2]: Pulsing with different electric signal curves but at the same location results in X22-Correlations near to 1.

Disadvantage: At least signals at two sensors are necessary. In the case of more than two sensors a lot of cross-correlation values may be calculated.

### *2.3 Clustering based on X22-Correlation*

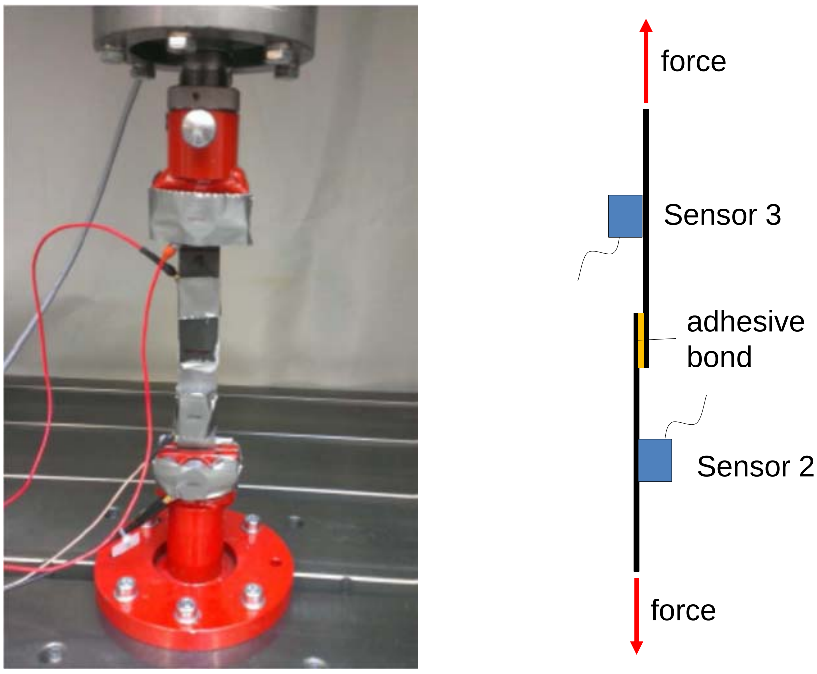
A simple clustering process, called X22-Clustering, based on X22-Correlation is used to identify groups (clusters) of similar events. Events with large Direct Correlation have very similar transient recorder curves and have also large X22-Correlation. Therefore, in a first step events with very large Direct Correlation are grouped together and called equivalent events. Only representative events of such groups of equivalent events are processed in the X22-Correlation analysis. This saves a lot of computational power when a large number of events with nearly identical signal curves arise. Events with X22-Correlation larger than a threshold value are considered as similar. A X22-Cluster is generated if two similar events are found, and each event which is similar to at least one event in a cluster is grouped to the cluster. This means that not every event in the cluster is similar to every other event in the cluster. Like in a mesh, events are tied together. Sometimes this seems not to be plausible because events are found in a cluster which show relative small X22-Correlation.

## 3. Analysis of AE-signals during testing of adhesive bonds

Within a bachelor theses [4], acoustic emissions were aquired during testing of adhesive bonds.

**Table 1.** Tested adhesives

| Shortcut | Name and producer | Description |
|---|---|---|
| X60 | X60 strain gauge glue from „Hottinger Baldwin Messtechnik GmbH (HBM)“ | 2-component adhesive, consisting of a liquid and a powder component; based on methyl-methacrylate |
| Z70 | Z70 strain gauge glue from „Hottinger Baldwin Messtechnik GmbH (HBM)“ | One component adhesive based on cyanacrylat |
| EF300 | HU PLUS ENDFEST 300 from “UHU GmbH & Co. KG” | Epoxy resin glue |
| Terostat-9220 | TEROSON MS 9220 from “Henkel AG & Co. KGaA” | MS-polymer glue |




**Pic. 3.** Arrangement for testing of adhesive bonds; left: photo [4]; right: principle arrangement.

Arrangement (Pic. 3): According to EN 1465 [5], two steel strips were bond by the investigated adhesives. These connections were tested afterwards in a tensile testing machine. Four acoustic emission sensors were applied. Sensors 2 and 3 were placed on the strips for acquiring signals from fracture. As guard sensors for filtering noise from loading equipment and clamping, sensors 1 and 4 were mounted on the clamped supports.

The whole investigation considered 4 types of adhesives (Table 1) and at least three samples with each adhesive were tested. Interesting behaviour according to X22-Correlation was found in the case of the relative brittle adhesives X60 and EF300. Therefore, some of these results are presented here. Both adhesives showed 100% adhesive failure (Pic. 4); X60 fractured almost completely at one side of the adhesive layer, EF300 fractured partly at one and partly at the other side.

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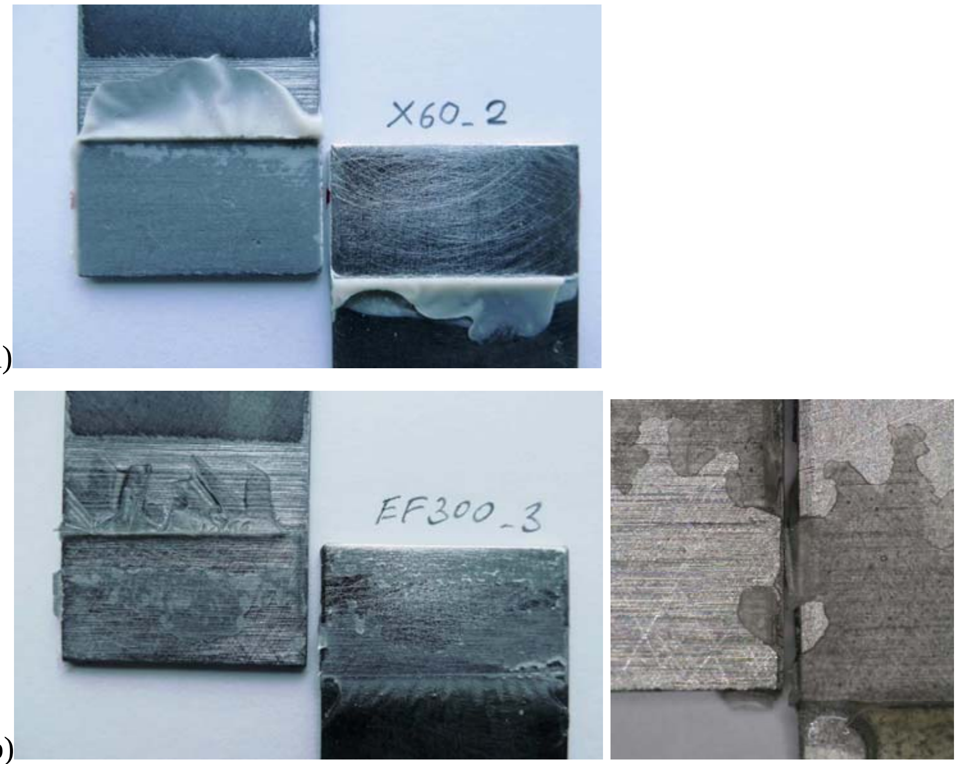



**Pic. 4.** Fracture surfaces; a) X60_2; b) EF300_3.

*3.1 Analyse of sample X60_2*

X22-Clustering according to paragraph 2.3 was used to identify groups (clusters) of similar events (Table 2). Three clusters with a considerable number of events (clusters 1, 2, and 4) were identified. Table 2 shows the total number of events within these clusters and the number of “equivalent events” within the clusters, which were tied to outers due to large Direct Correlation. The relatively small number of equivalent events show that grouping is enabled here by X22-Clustering, which means that the source functions of the grouped events differ in most cases.

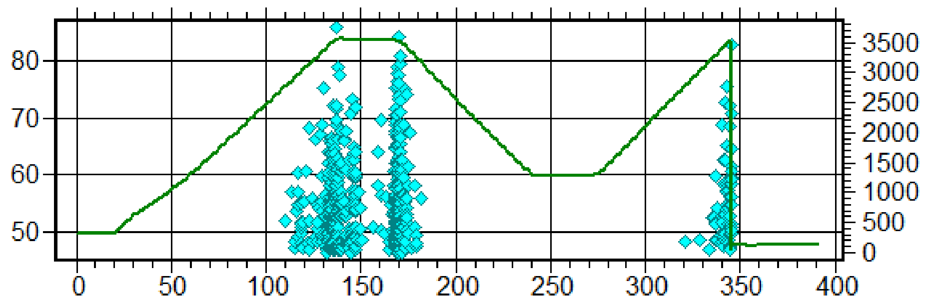
Pic. 5 shows the distribution of the events of cluster 1 within the experiment. It is clearly seen that this cluster is active during the whole damage process of the sample.

Two of the events in this cluster, event 2 and event 8, are further analysed. The signal curves acquired by the transient recorder (Pic. 6) are different but of similar type. This is reflected by the relative small Direct Correlations and the large X22-Correlation (Table 3).

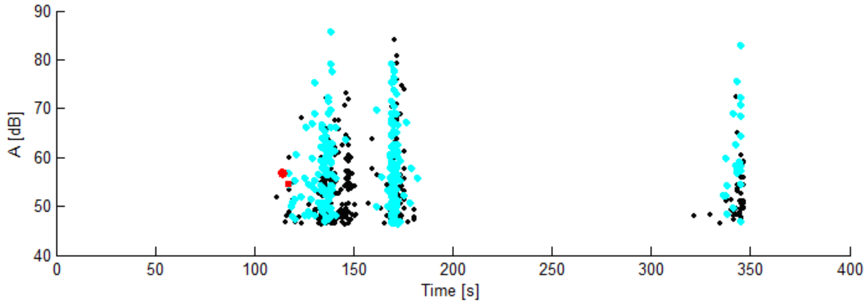
The identification of relative large X22-clusters is in agreement with the fracture surface (Pic. 4 a): Due to the continuous adhesive fracture at one side of the adhesive, similar fracture events are expected.

**Table 2.** X22-clusters with considerable numbers of events for X60_2

| Cluster Nr. | Total Number of events in clusters | Equivalent events | Remarks |
|---|---|---|---|
| 1 | 279 | 35 | activity starting at 80% of max load, continued during unloading and restarted below max force before final fracture |
| 2 | 46 | 1 | One event at 85% of max. load, few events just before and after first unloading, events at reloading starting before reaching the previous maximum up to the max load |
| 4 | 45 | 14 | Activity starting just before first holding time and ends during holding time |




a)

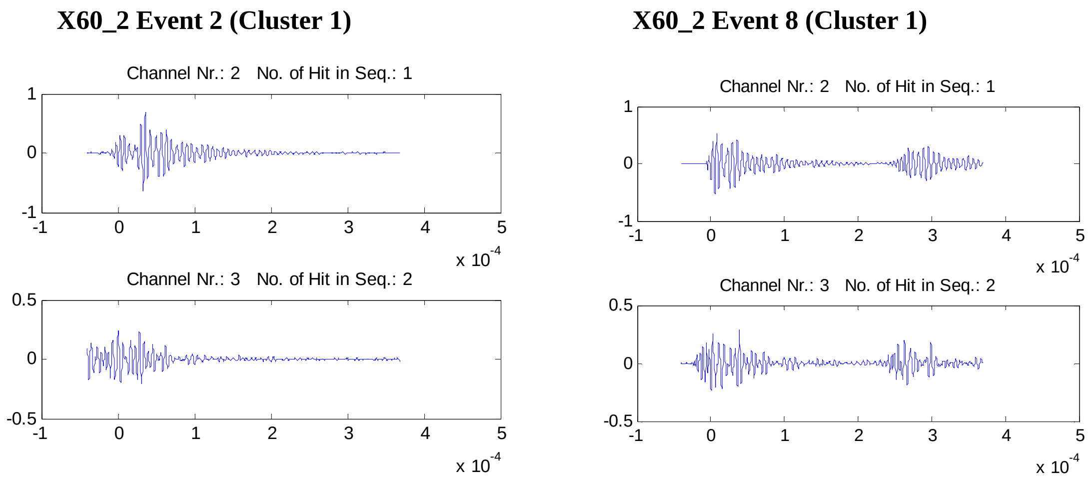



b)

**Pic. 5.** Results of X60_2: a) Total force and Amplitude at first hit sensor vs. time; b) Amplitude at first hit sensor vs. time – events from cluster 1 marked; red: events 2 and 8 which are further analysed; cyan: all other events of cluster 1.

**Table 3.** Comparing events 2 and 8 from X60_2 (both are elements of cluster 1)

| | |
|---|---|
| Direct correlation at Sensor 2 | 0.74 |
| Direct correlation at Sensor 3 | 0.64 |
| X22 - correlation | 0.937 |




**Pic. 6.** Transient recorder data from X60_2: two events of cluster 1 compared (voltage at sensor output in mV vs. time in s).

### *3.2 Analyse of sample EF300_3*

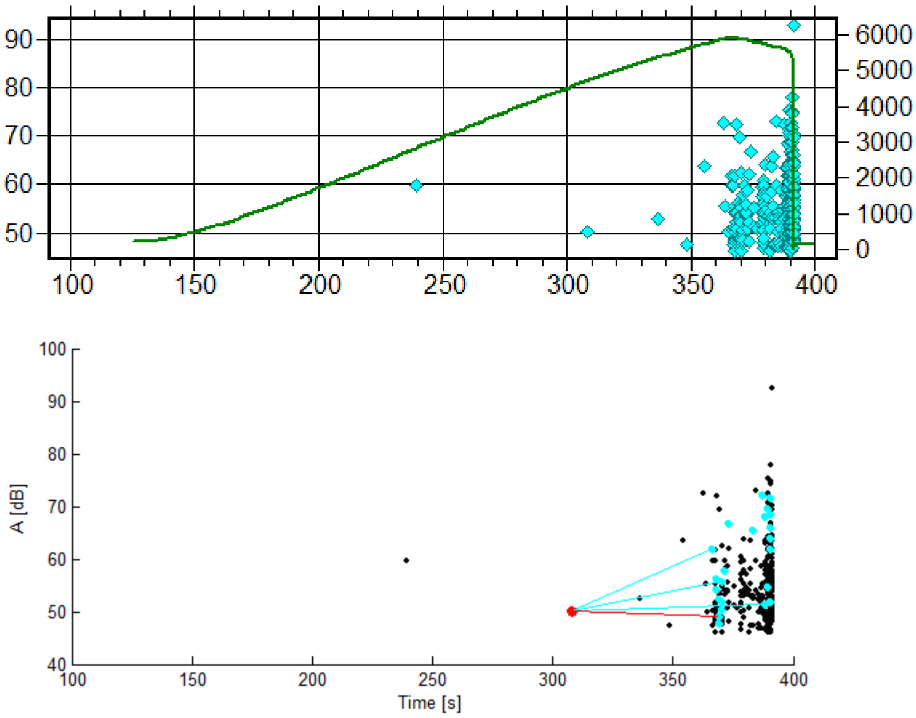
For this sample X22-Correlation according to paragraph 2.3 result in five clusters with a considerable number of events (Table 4), but the number of events within the clusters is much smaller than for X60_2. Only few equivalent events are within the clusters.
Pic. 7 shows the distribution of the events of cluster 1 within the experiment. The first event of cluster 1 arises at about 80% of the maximum load; the rest of the events of this cluster are acquired at the maximum load and afterwards (Pic. 7).

Also here two events, event 2 and event 36 of cluster 1 (marked in Pic.7), are further analysed (Pic. 8), showing same type but different transient recorder curves. This is reflected by the values for Direct Correlations and X22-Correlation in Table 5.

The identified smaller numbers of events within the X22-Clusters are plausible when comparing the fracture surfaces of both samples (Pic. 4): In comparison to sample X60_2, fracture of EF300_3 took place partly at one side and partly at the other one. In this case less similar fracture events are expected.

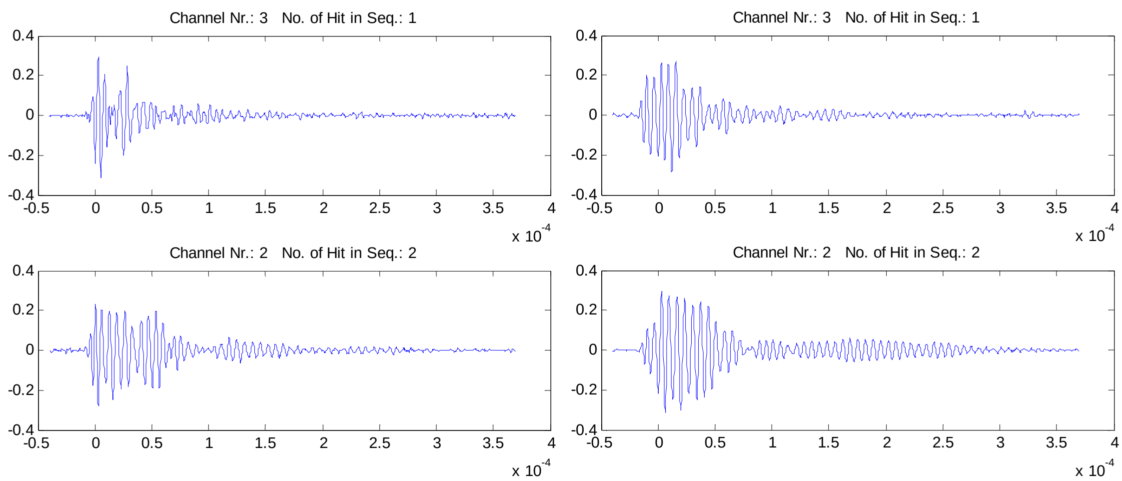
**Table 4.** X22-clusters with considerable numbers of events for EF300_3

| Cluster Nr. | Total Number of events in clusters | Equivalent events | Remarks |
|---|---|---|---|
| 1 | 24 | 0 | One event at 80% of maximum load, other events at maximum load and afterwards |
| 8 | 14 | 2 | Events after maximum load before total facture |
| 9 | 10 | 0 | Events before total fracture |
| 13 | 14 | 0 | Events before total fracture |
| 14 | 13 | 6 | Events before total fracture |




**Pic. 7.** Results of EF300_3: a) Total force and Amplitude at first hit sensor vs. time; b) Amplitude at first hit sensor vs. time – events from cluster 1 marked; red point: events 2; cyan: all other events of cluster 1; red line: connection of event 2 with 36; cyan lines: connect events with large X22-Correlation to event 2.

**EF300_3 Event 2 (Cluster 1)** **EF300_3 Event 36 (Cluster 1)**




**Pic. 8.** Transient recorder data from EF300_3: two events of cluster 1 compared (voltage at sensor output in mV vs. time in s).

**Table 5.** Comparing events 2 and 36 from EF300_3 (both are elements of cluster 1)

| | |
|---|---|
| Direct correlation at Sensor 2 | 0.72 |
| Direct correlation at Sensor 3 | 0.85 |
| X22 - correlation | 0.96 |

### *3.3 Other glued samples from testing of adhesive bonds*

The other samples of X60 showed the same type of fracture as the sample X60_2; also relative large X22-Clusters were identified. The results of the other sample of EF300 are similar to the ones of EF300_3 and support the given conclusions.

In the case of the adhesive Z70 also the bonding between metal and adhesive failed, but the areas of single fracture surfaces were much smaller than in the case of EF300. As expected from the results above, the identified X22-Clusters contain only small numbers of events.

The last adhesive, Terostat-9220, is a very tough adhesive with large strain to rapture. In this case, only few acoustic emission events were acquired before the maximum load, and after the maximum load the amplitudes of the acquired acoustic emission signals were relative small. No useful X22-Clusters were identified for these tests.

## 4 Other Application of X22-Correlation

Grouping of events from friction was thought to be a promising application of X22-Correlation. Events from the same location with the same radiation characteristic but different source function would be expected. It was tried to group friction events during pressure cycling of a threaded hydraulic accumulator. In this case only a large number of events with almost equivalent transient recorder curves (large Direct Correlation) were grouped together – X22-Correlation did not help.

## 5. Conclusion

No large X22-Clusters could be identified within acoustic emission acquired from a defect during pressure testing [3], which means that large groups of events with same radiation characteristic and transfer function did not exist even though a large defect were present. This seems to be plausible because, as shown in [1, 2] with pencil lead breaks, events have to be within few millimetres to have large X22-Correlation. The length of the defect in this test was about 300 mm and also varying radiation characteristic is expected in such situation. This agrees with the results described in paragraph 4 of this paper, where X22-Clusters with larger numbers of events were only identified if adhesive connection failed at one side of the adhesive. In such situation events with equal radiation characteristic and very near to one another are expected.

## References

[1] F Rauscher, 'Acoustic Emission Events with Similar Transfer Functions', 29th European Conference on Acoustic Emission Testing (EWGAE), Vienna, September 2010 (www.ndt.net).

[2] F Rauscher, 'Acoustic Emission Events with Similar Transfer Functions', J. Acoustic Emission, 28 (2010).

[3] F Rauscher, 'Using X22-Correlation for Sub-clustering and Relative Location of Acoustic Emission Signals', 30th European Conference on Acoustic Emission Testing (EWGAE), Granada, September 2012 (www.ndt.net).

[4] D Mandl, 'Schallemissionsmessung an Klebeverbindungen', Bachelorarbeit an der Technischen Universität Wien, Vienna, 2014

[5] EN 1465, 'Adhesives - Determination of tensile lap-shear strength of bonded assemblies', CEN European Committee for Standardization, July 2009