# Contribution to the Three-Dimensional Location of Acoustic Emission Sources During Local Monitoring of a Crack

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## INTRODUCTION

In reactor technology, acoustic emission is conventionally used for the global surveillance of reactor components. Regions of activity can be detected but the precise position of the sources remains in general uncertain. We have developed in the last years the technique of local monitoring of a known crack (Tirbonod and Hanacek, 1989a), to circumvent this shortcoming and to locate the position of the sources three-dimensionally. Full advantage of this technique was achieved by broadening the frequency spectrum of the measuring system from the conventional upper limit of 1 MHz up to 5 MHz. Thereby, the information on the signals (e.g. form of the signal or frequency content) could be improved.

The measurement system was designed to measure acoustic emission signals at the in-service temperature of a nuclear reactor pressure vessel (310 °C) in a broad frequency band. Transducers from Interatom, FRG, using a piezoelement of $LiNbO_3$ fulfil these requirements: they work at temperatures up to 400 °C, are broadband with variations of amplitude better than ± 10 dB between 500 kHz and 5 MHz and are sensitive to displacements of $10^{-14}$ m; unfortunately their damping seems to be insufficient. The 4-channel recording system includes a low noise charge amplifier, a high-pass filter (100 kHz), a main amplifier and an antialiasing low-pass filter; the gain after connection to the transducer is fixed to 40 dB. The trigger unit which has to detect the events in the continuous measuring signal works on the basis of a floating threshold level. The signals of the events are digitized and stored via a transient recorder (storage length of 2048 words per channel, resolution of 10 bits, sampling frequency of 20 MHz, 15 events/s) and a computer on a magnetic tape (1 event/s) for off-line processing.

In this study, we report on the accuracy of the three-dimensional source location by the local monitoring technique. Several factors which influence the accuracy are discussed and shown by laboratory experiments. The technique of local monitoring of a known crack is applied to a thermal shock and a fatigue test on pressure vessels.

## LOCATION PROCEDURE

The measurement array includes 4 transducers, the first one in the epicenter of the known crack, the other ones at the vertices of an equilateral triangle around the first transducer on a radius of 80 mm (Figure 1). This setup allows for a three-dimensional location of the sources along the crack, for an improved information on the sources mainly from the response of the first transducer and for guarding the measurement array from events or noise from outside the surveyed area. The position of the sources is determined by the differences in the arrival times of the signals. The start of the signal is assumed to be formed by waves coming directly from the source, i.e. either the longitudinal wave or the surface wave:

$$\Delta t_{i1} \cdot c = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} \qquad [1]$$

| where : | |
|---|---|
| $\Delta t_{i1}$ | difference in the arrival times at transducer $i$ and transducer 1 |
| $i$ | transducers 1 to 4 |
| $c$ | known phase velocitiy of the longitudinal wave (6 mm/$\mu$s) or the surface wave (3 mm/$\mu$s) |
| $x, y, z$ | unknown position of the source |
| $x_i, y_i, z_i$ | position of the piezoelement of transducer $i$ |

In the case of a three-dimensional location by longitudinal waves, the non-linear equation system [1] is solved directly by use of a hybrid algorithm (More et al., 1980). However if the source determined by longitudinal waves is located near to the surface on the side of the transducers or if no solution of equation system [1] is reached, a surface wave is assumed; a solution would generally be obtained by a reduced phase velocity. Since the depth $z$ is already known, there is a redundancy in equation system [1], and the error in locating the source is reduced by means of the least square procedure. The direction to sources outside the measurement array is determined well while the distance to them is roughly guessed.

## ACCURACY OF SOURCE LOCATION

Accurate source location requires a precise definition of the differences in time. The differences in time have to be defined in the local monitoring technique by the arrival times; location by the times at peak amplitude, as it is usual with the conventional global surveillance systems, leads to unrealistic results. The initial edge of the signal has to be identified by inspection to surely distinguish events from noise and to consider numerical inaccuracies due to the digitizing of the signal as well errors in the automatic determination of the arrival times. Pencil fracture tests on a 118 mm thick plate without cladding and on a 124 mm one with a 6 mm thick cladding were performed in the non-noisy environment of the laboratory. An accuracy in the arrival times of ± 0.15 $\mu$s, which is mainly dependent on the precision of their definition at large incidence angles, was achieved. This leads to a maximal scatter of the located sources in the planar coordinates of ± 2.8 mm and ± 7.8 mm in depth (Figure 3). The systematic deviation from the nominal depth is traced back to the incidence angle of the wave field to the transducers.

The influence of the incidence angle and of the finite dimension of the transducers on the arrival time of the wave was studied by comparing the values of a point transducer from NBS and of our transducer from Interatom. The difference in arrival times of signals generated by pencil fractures in the middle between the transducers on a 100 mm thick plate was determined for different distances of the transducers and is shown in Figure 4 as function of the incidence angle. A similar relationship with the incidence angle was obtained by high frequency content signals generated by laser pulse. The laser pulses were applied perpendicularly to the curved surface of one half of a cylinder with radius 100 mm on different angles to the transducer which was fixed in the center on the plane surface. The experimentally found time shift may be interpreted thus, that the first point of the piezoelement hit by the wave front is responsible for the start of the signal. Two possible wave rays within the transducer are considered (Figure 2): The direct ray fits better the large incidence angle of the laser pulses, the diffracted ray matches the pencil fractures. The determination of the valid correction function and its influence on the accuracy of source location (Figure 3) is subject to further investigation.

Factors which influence the accuracy of source location systematically:

- The position of the transducers is defined in general quite well, but it is very important to take the curvature of the pressure vessel into consideration.
- The phase velocity is assumed to be constant; this is valid since the sources are localized in the near field. The phase velocity is assumed to have a constant value of 6 mm/$\mu$s for the longitudinal wave. However, it is known that the phase velocity is reduced by about 5 % with

a temperature increase from room temperature to 300 °C, the in–service temperature of reactor pressure vessels.

- The assumption of a direct wave between source and transducer holds for a homogeneous material. The presence of a crack would defract the waves and increase the paths between source and transducers if they cross the crack. However, the actual size of the crack cannot be determined by a 4–channel recording system, since this allows only for to determine 3 unknowns for which the ccordinates $x, y, z$ have been chosen.

The accuracy for different cases and a 25 mm deep and 100 mm long crack in a 135 mm thick component are shown in the following table. The standard setup was chosen (Figure 2) together with sources along the positive $x$ axis and point source as well as point transducers. In this theoretical example, the given differences Δ represent the maximal errors.

| Case | Δx [mm] | Δy [mm] | Increase in depth Δz [mm] |
|---|---|---|---|
| Statistical error: | | | |
| - Signal start ± 0.15 $\mu$s | ±2.8 | ±1.4 | ±7.8 |
| Systematical errors: | | | |
| - Position of transducer 1 | | | |
| $x_1$ + 1.0 mm | +1.2 | - 0.1 | +3.4 |
| $y_1$ + 1.0 mm | - 0.1 | - 0.1 | - 0.1 |
| $z_1$ + 1.0 mm | +2.7 | - 0.1 | - 7.3 |
| - Curvature with radius 2500 mm | +2.7 | - 0.1 | - 7.3 |
| - Phase velocity reduced by 5 % | +0.1 | - 0.2 | +7.0 |
| - Presence of a crack | | | |
| Source at $y = +0.1$ | - 2.2 | +1.5 | - 5.6 |
| Source at $y = -0.1$ | - 3.8 | - 5.1 | - 10.0 |

## THE LOCAL MONITORING TECHNIQUE DURING A THERMAL SHOCK ON THE PRESSURE VESSEL HDR

The thermal shock experiment was performed on the decommissioned hot steam reactor pressure vessel HDR at Karlstein, FRG. The very severe loading condition of a long term thermal shock with superimposed pressure was investigated regarding stable crack extension. The experiment started with the pressure vessel under in–service conditions (310 °C, 10.6 MPa). The controlled cooling with cold water resulted after about 30 minutes in a temperature of 80 °C at the interface between the ferritic base material and the austenitic cladding. The stop of the water inflow gave rise after a further 30 minutes to the in–service condition again. A 31 mm deep crack was locally monitored by acoustic emission.

At the beginning of the experiment, we considered only events originating from the crack. The noise from outside the surveyed area is eliminated in this guard mode through the condition that an event has to hit first the central transducer. No events were registered at the beginning of the cooling phase. The release of the guard mode resulted in the registration of noise whose amplitude is increased to the end of the cooling phase and ceased to the end of the heat–up phase. 20 events could be detected in the heat–up phase. These events were superimposed on the noise of the same magnitude. Their separation was possible in the off–line processing by a high–pass filter set at 500 kHz: spectral analysis has shown for events a pronounced peak of the amplitude at about 1 MHz and for the noise a continuously decreasing amplitude with increasing frequency.

The sources were localized on the outer surface by surface waves, but no event emanated from the monitored crack (Figure 5). The fact that the crack was inactive was confirmed by the electric potential method and by ultrasonics testing, where also no crack extension was observed. The source mechanisms of the observed events cannot be explained at the moment.

## THE LOCAL MONITORING TECHNIQUE DURING A FATIGUE TEST ON THE PRESSURE VESSEL ZB2

Acoustic emission from an artificial crack of length 100 mm and of depth 24 mm was observed under realistic conditions in the pressure vessel ZB2 (Project ZB2 of the Bundesministerium für Forschung und Technologie, FRG). The pressure vessel had a diameter of 2000 mm and a wall thickness of 134 mm. The base material of the segment with the crack was made out of a reactor steel (A533B) and the cladding out of an austenitic steel. The fatigue test included 14170 cycles at 50 °C in the pressure range 2.5 MPa to 21 MPa with a loading rate of 14 MPa/min and an unloading rate of 70 MPa/min. The crack grew by 2.7 $\mu$m per cycle. Acoustic emission measurements were performed over a total number of 4700 cycles, 4200 signals were recorded (Tirbonod and Hanacek, 1989a).

Most of the signals were recurrent. These recurrent signals are grouped in classes, each characterised by a similar form of the signal and the same location of their sources inside the location error. 22 classes of recurrent signals were found. The sources are differently distributed along the artificial region of the crack according to the loading phase (Figure 6a). The sources at loading are shifted from the center of the artificial crack towards its right end as the experiment went on; those at unloading are situated in the left of the artificial crack. The depth of the sources does not exceed the initial depth of the crack inside the location error (Figure 6b). The sources active at unloading can be related to a friction mechanism; at the moment it remains a open question, if those at loading are caused by crack growth or by decohesion between asperities (Tirbonod and Hanacek, 1989b).

Only one source of a non recurrent signal is located in depth outside the artificial crack (by 19 mm at cycle 9422, Figure 5b). Its position agrees well with the calculated crack front. Therefore, it could give evidence of crack growth.

## CONCLUSIONS

- The local monitoring technique allows for an accurate three–dimensional location of events on the expense of surveilling a known crack and a limited region.
- An accuracy of better than ± 2.8 mm in the planar coordinates and of ± 7.8 mm in depth is typical for our local monitoring system and a 135 mm thick plate. Factors which increase the precision of defining the arrival times would reduce this statistical error. The systematic error is dependent on the finite size of the transducers.
- The storage of the whole signal is important for the inspection of the arrival times of the signal; badly defined arrival times increase the location error. The storage is also helpfull in the discrimination of events through filtering in the off–line processing.

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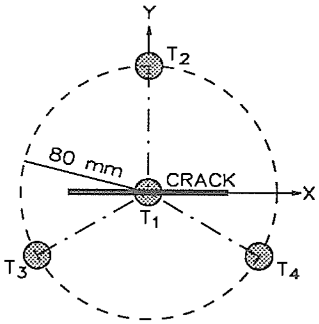

Figure 1: Standard setup for the local monitoring of a known crack.

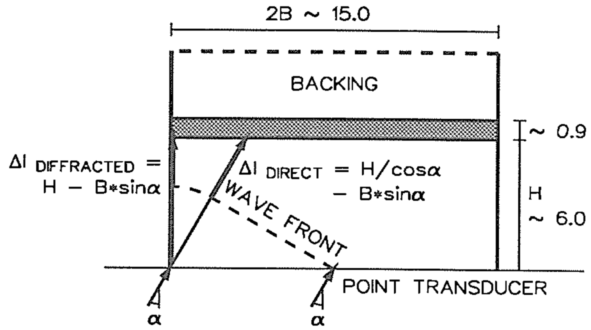

Figure 2: Schematic presentation of the Interatom transducer.

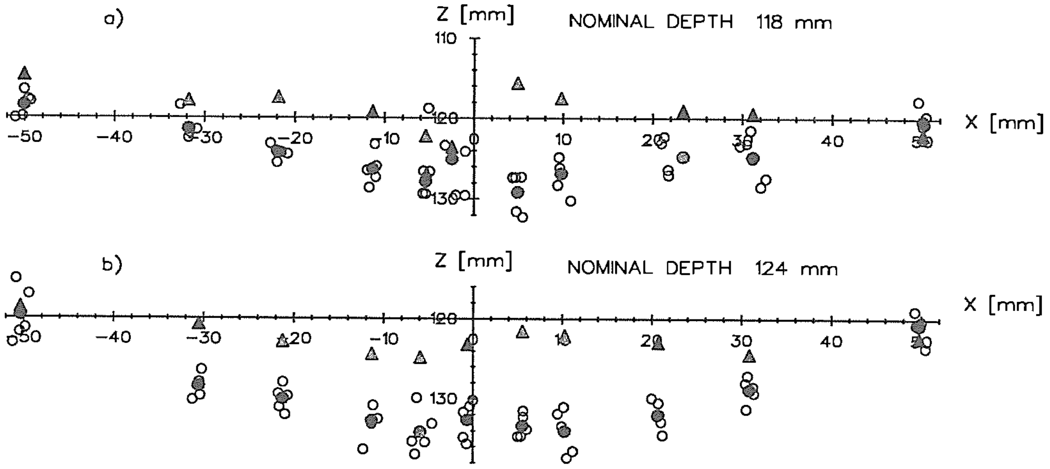

Figure 3: Pencil fracture experiments on a
a) 118 mm thick plate without cladding,
b) 124 mm thick plate with 6 mm cladding.

○ Measurement
● Average
▲ Corrected average (direct wave)

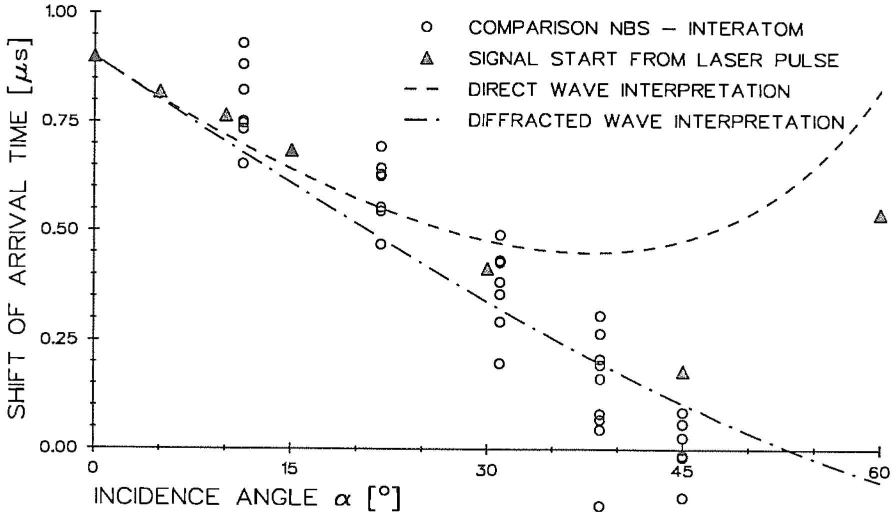

Figure 4: Influence of incidence angle on the definition of arrival time.

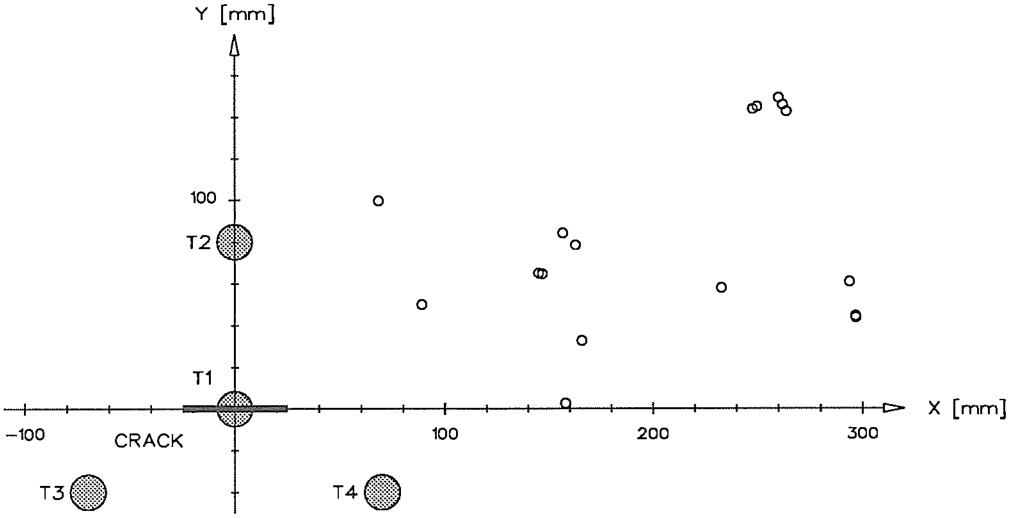

Figure 5: Source location at the outer surface of the HDR pressure vessel due to a thermal shock.

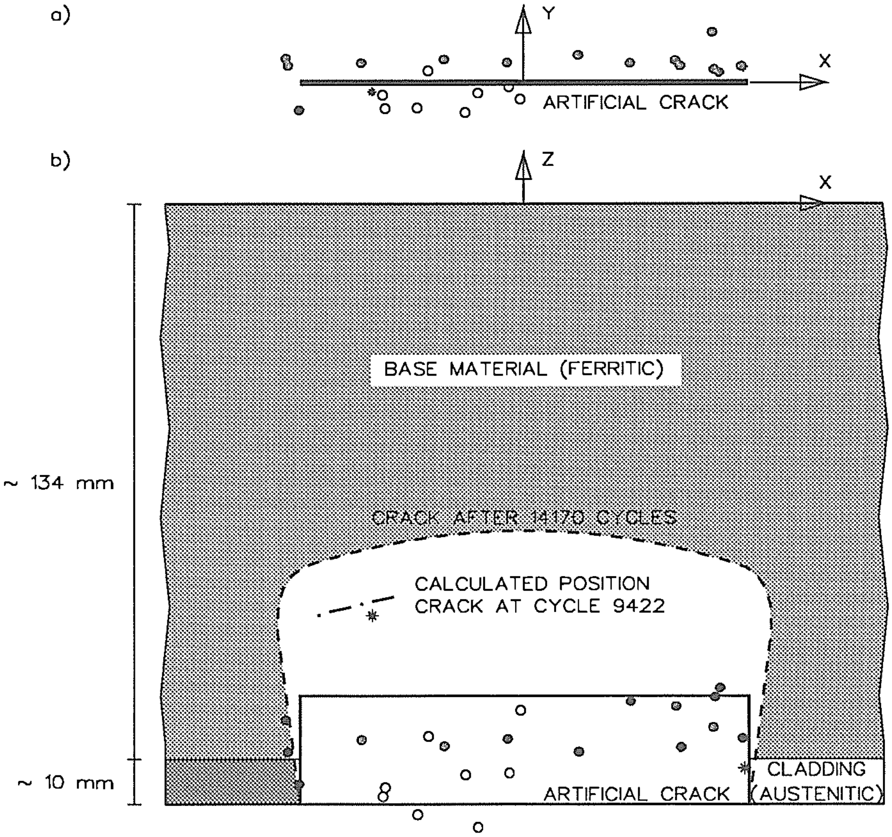

Figure 6: Three–dimensional location of acoustic emission sources during the fatigue test on the pressure vessel ZB2.

a) in the planar coordinates $x$, $y$,
b) in depth $z$.

| | |
|---|---|
| ◉ | Sources active during loading |
| ○ | Sources active during unloading |
| $*$ | Non recurrent signals during loading |