TIME DIFFERENCES UNCERTAINTY INFLUENCE ON ACOUSTIC EMISSION SOURCE LOCATION ACCURACY

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ABSTRACT

Acoustic emission (AE) is a non-destructive testing method using acoustic, mostly ultrasonic, waves emitted by AE sources and propagating in structure to find out desired information about the tested construction or sample state. The AE source location is its basic (and very important) parameter. Most of location algorithms use time differences of AE signal arrival times from the source to different transducers and acoustic wave propagation velocity as input data. However, the parameters are often difficult to obtain in real conditions, especially out of laboratory and in the working conditions where acoustic noise is presented. Main goal of this paper is to analyze influence of time differences uncertainty (i.e. errors in the detected times) and the elastic wave velocity uncertainty on AE source 2-D location accuracy. The analysis will be done for a classic triangulation location algorithm, but we expect very similar results for any location algorithm based on time differences (e.g. neural networks location algorithm), because the problem geometry and location equations are the same.

KEYWORDS: Acoustic emission, source location, location error.

INTRODUCTION

Acoustic emission (AE) is a non-destructive testing method, which is applicable to structure (e.g. planes, bridges and pressure vessels) and industrial process (stamping, cutting) state monitoring in the working conditions. The AE method using acoustic, mostly ultrasonic, waves emitted by acoustic emission sources and propagating in structure to find out desired information about the tested construction or sample state (e.g. sample is undamaged or sample is damaged and the defect coordinates). It is possible, because the AE sources are usually caused by material structure changes, which usually appear if some defects or cracks in the tested structure are presented.

A classic triangulation algorithm is still mostly used method for 2-D AE sources location. The algorithm computes polar coordinates r, α of AE source using analytical formulas. Time differences Δt of AE signal arrival time from the source to different transducers are input data of triangulation location algorithm together with elastic wave velocity. Analytical formulas are known for thin isotropic plate. If the plate is anisotropic, analytical formulas generally don't exist. An alternative location method must be used in anisotropic materials (an artificial neural network location method [1-3] or a crosscorelation location method [6] were published recently). But the time differences Δt are still used: in the neural network method directly, in the crosscoralation method indirectly.

Recorded AE signals are without noise and with only small dispersion and attenuation of acoustic waves ideally. It is quite easy to find information about a defect in the structure and about the defect location in the ideal case. Unfortunately in the real world, especially out of laboratory and in composite material measurements, conditions are far from ideal. It's easy to imagine acoustic noise accompanying AE measurement of metal plate stamping or AE testing of aircraft parts during a fatigue test. Uncertainty in computed time differences or even corrupted location algorithm input data appears as the difficult measurement conditions result.

The problem of 2-D location algorithm inaccurate input parameters (it is time differences and elastic wave velocity) influence on acoustic emission source location accuracy will be discussed in this paper. Location formulas will be analyzed and solvability conditions will be formulated. And last but not least the location error caused by the time differences inaccuracy will be computed using computer simulations and drawn in pictures and graphs.

2-D TRIANGULATION ALGORITHM

Classical 2-D AE sources location algorithm, so called triangulation algorithm, is well known in many versions [1], [6]. The simplest one corresponds to AE transducers configuration plotted in fig.1. Transducers no. 1, 2 and 3 shape rectangular triangle, distances of transducers 1, 2 and 1, 3 are the same – equal to constant a. S is an AE source of unknown polar coordinates r, α (x, y in Cartesian coordinates) , v is elastic wave velocity.

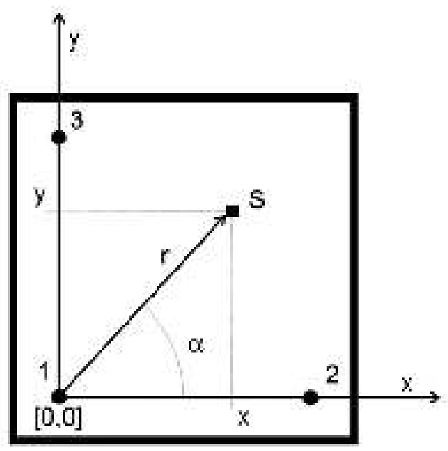

Fig.1: 2-D AE source location schema.

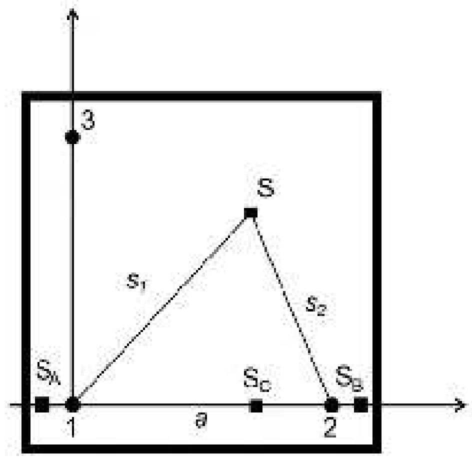

Fig.2: Maximum time difference proof schema.

If the time difference of AE signal arrival between transducers 2 and 1 Δt_{21} is marked t_1 and the time difference of AE signal arrival between transducers 3 and 1 Δt_{31} is marked t_2, then the unknown AE source coordinates are given by formulas

$$r = \frac{A_1}{2(a\cos\alpha + vt_1)} = \frac{A_2}{2(a\cos\alpha + vt_2)}, \tag{1}$$

$$\cos(\alpha - \psi) = K, \tag{2}$$

where variables A_1, A_2, ψ and K are computed using formulas

$$K = -\frac{v}{a}\frac{A_2 t_1 - A_1 t_2}{\sqrt{A_1^2 + A_2^2}}, \tag{3}$$

$$\tan\psi = -\frac{A_1}{A_2}, \tag{4}$$

$$A_1 = a^2 - (vt_1)^2,\ \ A_2 = a^2 - (vt_2)^2.$$

It is simple to proof the theorem: if the input parameters t_1, t_2 and v are accurate, then maximum admissible time difference depends on AE transducers distance a and velocity v only and it is less or equal to a/v

$$|t_1| \le \frac{a}{v}, \qquad |t_2| < \frac{a}{v}, \tag{5, 6}$$

(the sign < in (6) results from the formula (4), because $A_2 \neq 0$).

Proof: For any AE source S_C between 1 and 2 transducers (see fig. 2) absolute value of distance differences from the S_C to transducer 2 and from the S_C to transducer 1 is less or equal to a,

$$|\Delta s_{21}| \le a. \tag{7}$$

The formula (5) is formula (7) divided by v, so the formula (5) is true for any AE source between 2 and 1 transducers. If AE source and the sensors 1, 2 are in line and the source is outside of sensors 1, 2 abscissa (S_A or S_B position), then absolute value of AE source distance differences from S_A (S_B) to transducer 2 and from S_A (S_B) to transducer 1 is just equal to a (difference is $+a$ for the S_A source, $-a$ for the S_B source). It implies equation $|t_1| = a/v$, so that the formula (5) is true for any AE source in transducers line. If we have an AE source S that is not in the transducers line, points 1, 2 and S (see fig. 2) generate a triangle. For any triangle in plane sum of two sides lengths must be greater than the third side length

$$(a + b > c) \wedge (a + c > b) \wedge (b + c > a). \tag{8}$$

Let's mark $s_2 - s_1 = \Delta s_{21}$. If $s_2 \ge s_1$ we use the formula (8) and obtain estimation (see fig. 2)

$$s_1 + a > s_2 \Rightarrow a > s_2 - s_1 \Rightarrow a > \Delta s_{21} \Rightarrow \frac{a}{v} > \Delta t_{21} = t_1 = |t_1|, \tag{9}$$

because t_1 is positive. If $s_2 < s_1$ we use the formula (8) also and obtain estimation

$$s_2 + a > s_1 \Rightarrow a > s_1 - s_2 \Rightarrow a > -\Delta s_{21} \Rightarrow \frac{a}{v} > -\Delta t_{21} = -t_1 = |t_1|, \tag{10}$$

because $-t_1$ is positive. So the formula (5) is true for any AE source in plane.

Formula (2) imply condition $|K| \le 1$ for the parameter K, because $|\cos\alpha|$ is ≤ 1 for all $\alpha \in R$. It is possible to qualify the condition using simple algebraic operations. The algebraic operations result is non-equation

$$0 \le A_1 A_2 (A_1 + A_2 + 2 t_1 t_2 v^2). \tag{11}$$

If the conditions (5), (6) are true, then $A_1 \geq 0$ and $A_2 > 0$. To come true the formula (11), the third factor must be positive or equal to zero,

$$A_1 + A_2 + 2t_1t_2v^2 \geq 0 \Rightarrow \left|t_1 - t_2\right| \leq \sqrt{2}\frac{a}{v}. \tag{12}$$

We have three conditions for input parameters of triangulation location algorithm expressed by the formulas (5), (6) and (12). In ideal case (it is input parameters t_1, t_2 and v are accurate, error free) the formulas (5), (6) and (12) are always valid (formula (12) proof is similar to the formula (5) proof), but it is not true if the input parameters are corrupted. Hence the formulas (5), (6) and (12) false is the first symptom of corrupted input parameters t_1, t_2 and (or) v.

It is known, that 2-D location of AE sources using 3 transducers is not unambiguous [5]. In fig. 3 two configurations of transducers are drawn. The first one is the same rectangular configuration as discussed above, the second one is equiangular triangle. There are visible areas of unambiguous location in both pictures (fig. 3). Any AE source in dark gray area has the same time differences t_1, t_2 as correspond source in light gray area and vice versa. The problem is usually solved by 4 transducers location (two different triplets of transducers are used), but theoretically it is not real solution. Area of unambiguous location is reduced to insular points, but it still exist. However, probability that we must locate such AE source is close to zero in the real world.

COMPUTER SIMULATIONS OF AE SOURCES LOCATION USING TRIANGULATION ALGORITHM AND INACURRATED INPUT DATA

Let's analyze typical 2-D location problem. We have thin aluminum plate of dimension 1000×1000×2 mm. In the center of plate are located three AE transducers in rectangular configuration (fig. 1), distance of transducers is a = 330 mm. Let's assume the transducers frequency range 50 – 1000 kHz and maximum sensitivity close to frequency 200 kHz.

The first triangulation location algorithm input parameter is elastic wave velocity v. But which velocity and which wave? In table 1 the most common wave velocities are summarized ([4]).

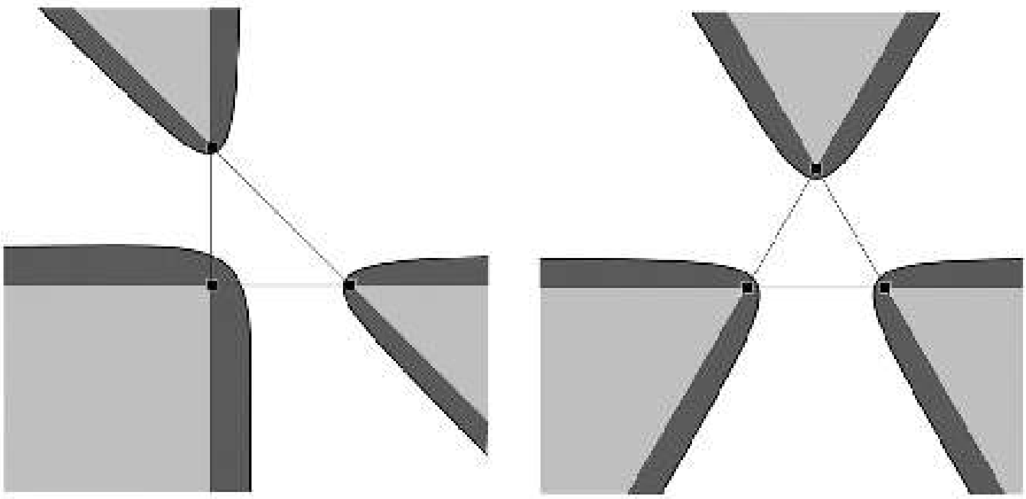

Fig.3: Ambiguity of 2-D AE sources location using 3 AE transducers.

wave or wave mode	symbol	Velocity [m/s]	wave or wave mode	symbol	Velocity [m/s]
Longitudinal wave	v_L	6374	Rayleigh wave	v_R	2906
Shear wave	v_S	3111	a_0 guided wave, f = 200 kHz	v_{a0}	2787

Table 1: Summary of elastic wave velocities in 2 mm thin aluminum plate.

We prefer antisymmetric guided wave mode a_0 in the table 1, because amplitude of symmetric guided wave mode s_0 is usually much lower. Higher guided wave modes are hig-frequency modes (compared to transducer maximum sensitivity frequency) and we don't think over them in this paper. Because the guided waves are dispersion waves, the wave velocity depends on the wave frequency. Therefore we must choose (main) frequency of a_0 guided wave to compute the wave velocity. With reference to the AE transducers frequency range we selected frequency f = 200 kHz. The guided wave velocity depends on sample (plate) thickness too. More dispersion effects are presented in thin plates and structures.

It is very easy to make mistake in a velocity measurement. Amplitudes of elastic waves and wave modes changed from AE event to AE event markedly and background noise is usually presented in AE measurement. The problem is especially serious once the AE events amplitudes vary strongly, e.g. in small or medium sized structures. It is real edge of classical AE method utilization.

An elastic wave or even a specific wave mode arrival detection in AE signal is a difficult problem, especially in signals with high background noise or in dispersive signals. That is the reason why time differences Δt are often inaccurate. What inaccuracy is "normal" or "typical"? In this paper we will suppose that the typical time differences error is equal to one or two periods of signal. If frequency 200 kHz is considered, than the error is from 5 to 10 µs. The considerations above give us bounds of triangulation location algorithm input parameters (velocity v and time differences t_1, t_2) values.

We performed computer simulations of AE source location using corrupted input parameters. In the formulas (1) – (4) we changed velocity v, time differences t_1, t_2 or both. In presented simulations the time differences were increased

$$t_1^{er} = t_1^{real} + er, \qquad t_2^{er} = t_2^{real} + er, \qquad er \geq 0, \tag{13}$$

where er is time difference error (5 or 10 µs usually), t_1^{real}, t_2^{real} are the accurate differences computed for AE source of $[x, y]$ Cartesian coordinates using formulas

$$t_1^{real} = \frac{\sqrt{(x-a)^2 + y^2} - \sqrt{x^2 + y^2}}{v}, \qquad t_2^{real} = \frac{\sqrt{x^2 + (y-a)^2} - \sqrt{x^2 + y^2}}{v}.$$

Location error l is Euclidean distance of the $[x, y]$ coordinates source and the point in plane computed using formulas (1) – (4). We reduced the continuous AE source location error into three discrete levels to simplify results of computer simulations. The first level corresponds to small location error (it means good location). The second level is a medium error (the location accuracy is adequate) and the third one is a big location error (poor location). In the following pictures white color is used for the small location error representation, light gray means the medium error and black corresponds to the big location error.

Bounds of three intervals were selected as follows:

- good location $|l| \le 33$ mm (10% of transducers distance),
- adequate location $33 < |l| \le 100$ mm (10-30% of transducers distance),
- poor location $|l| > 100$ mm.

The input parameters corruption occasionally makes for unsolvability of location problem using the analytical formulas (1) – (4). This situation we illustrate with dark gray. In all pictures rectangular triangle of AE transducers is plotted to improve the pictures lucidity.

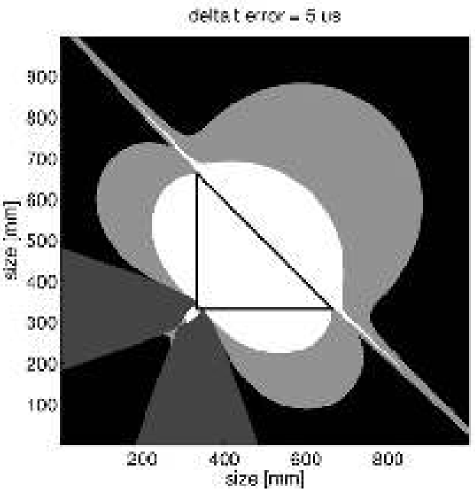

Fig.4: Location accuracy. Velocity v is accurate, time differences error is 5μs.

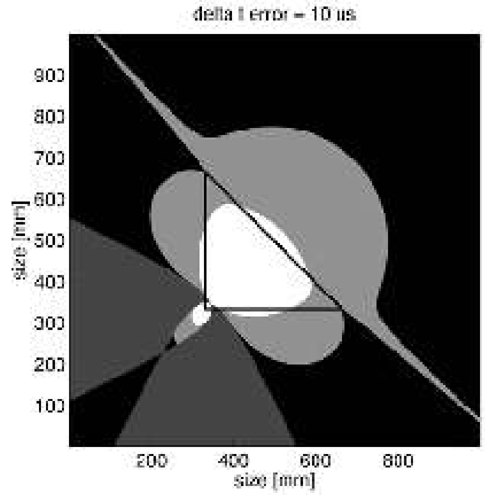

Fig.5: Location accuracy. Velocity v is accurate, time differences error is 10.5μs.

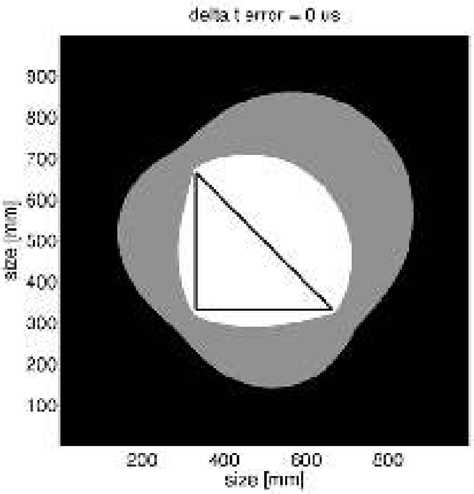

Fig.6: Location accuracy. Time differences are accurate, correct S-wave velocity is replaced with guided wave velocity.

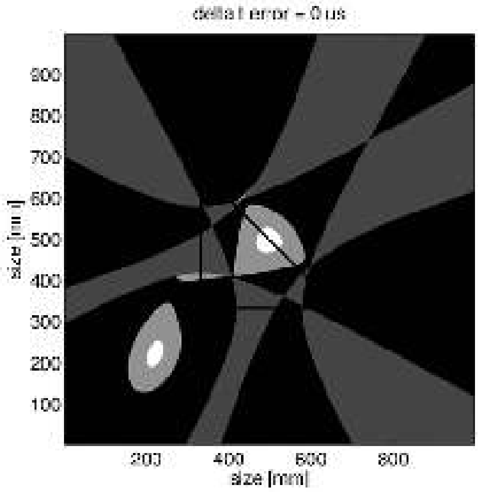

Fig.7: Location accuracy. Time differences are accurate, correct S-wave velocity is replaced with P-wave velocity.

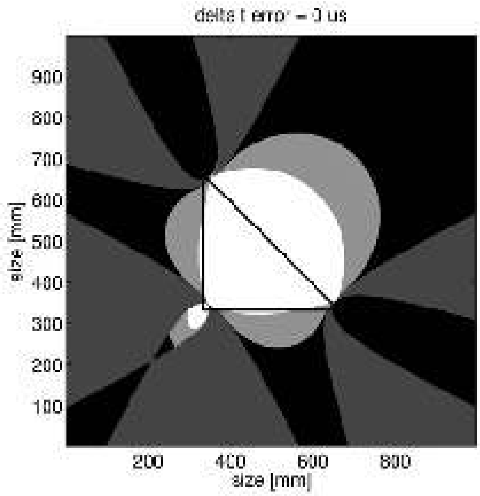

Fig.8: Correct guided wave velocity is replaced with S-wave velocity.

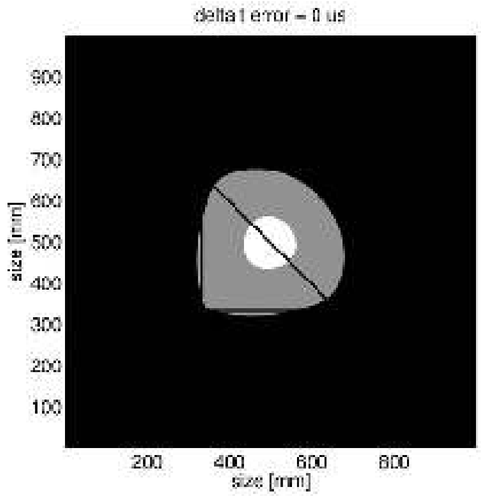

Fig.9: Correct P-wave velocity is replaced with S-wave velocity.

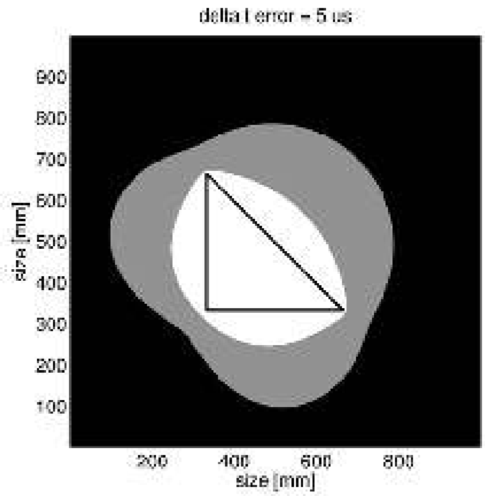

Fig.10: Time difference error is 5 µs, correct S-wave velocity is replaced with guided wave velocity.

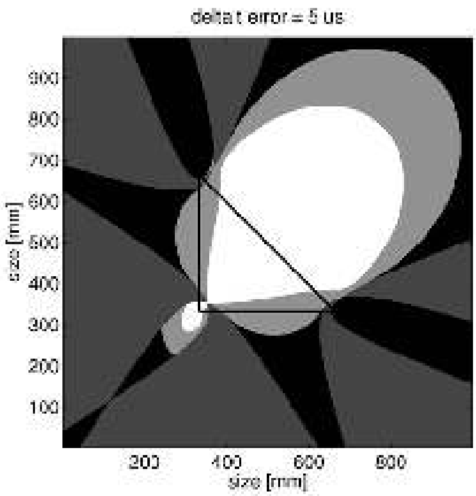

Fig.11: Time difference error is 5 µs, correct guided wave velocity is replaced with S-wave velocity.

The computer simulations results are plotted in fig. 4-11. In the fig. 4 and 5, used velocity *v* was accurate, only time differences were corrupted using the formulas (14). The error *er* was 5µs (fig.4) and 10 µs (fig.5). The fig.6-9 display four simulations of AE source location using accurate time differences but incorrect velocity *v*. Velocities of the longitudinal P-wave, the shear S-wave and the guided wave a_0 were confused. The figures 10 and 11 show the AE source location accuracy using completely corrupted input data – both time differences and velocity are inaccurate.

The computer simulations presented in fig.4-11 lead to important observations. It is clear that location of outside transducers triangle placed AE sources is usually poor or even impossible. Location error sources are the location ambiguity (see fig.3) and the location formula itself. The worst problem is overestimated velocity v (fig. 7, 8, 11). The conditions (5), (6) and (12) are not fulfil for many points in plate (dark gray areas in the figures) and close to AE transducers the location formulas become badly unstable (location error increasing rapidly). On the other hand accurate velocity and time differences error up to 10 μs brings satisfactory location accuracy in the transducers triangle. However, it is not true for greater time differences error, because location error growing quadraticaly with the time differences error.

CONCLUSIONS

In this paper short analysis of 2-D AE sources location formulas were done. Non-equations for maximum time differences of AE signal arrival were derived together with solvability condition of the location formulas. Second part of paper dissert on computer simulations of incorrectly parameterized AE sources location. The location formulas input parameters were corrupted in different ways and location error was drawn in pictures. The principal conclusions are:

- it is necessary to verify non-equations (5), (6) and (12) for any AE source located by classical triangulation algorithm. The formulas (5), (6) and (12) false is the first symptom of corrupted input parameters,
- velocity v overestimation is real killer of location accuracy, underestimation is fewer problem,
- location accuracy of AE sources placed in the transducers triangle is usually adequate, questionable areas are outside the triangle and close to the AE transducers,
- We recommend four AE transducers location to reduce areas of ambiguity location and fuzzy location principles utilization [2] in difficult conditions, such us high background noise, dispersion and strong attenuation of elastic waves, etc.

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