Estimation of the additive and multiplicative error of the standard algorithm of acoustic emission sources linear location

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Abstract. The paper deals with the results of the standard acoustic emission (AE) source linear location algorithm, which evaluates the location of developing damage in a steel sample under static load test to destruction. The linear location algorithm error is due to many factors: acquisition threshold of the AE signals and the dispersion properties of recorded signals, in particular, the dependence of the AE signal propagation velocity on its amplitude. According to the test results, the additive error in determining the time difference of arrival (TDA) of the AE signals to the transducers array is 52.8 μs and the average multiplicative error level is 0.67.

1. Introduction

Currently, a great number of dangerous industrial facilities with extended life are being in operation. The continuous monitoring systems based on physical methods of non-destructive testing are used to provide uninterrupted operation of such facilities. The most commonly used monitoring systems are the acoustic emission systems that provide the assessment of the level of the acoustic signal sources hazard that occurs in the process of generation and growth of the defects [1-4]. The standard linear location algorithm is used to identify the location of the developing damages. The use of the standard linear location algorithm consists in the calculation of the developing damages location based on the acoustic emission (AE) signal velocity (V) in the material of the test object and the time difference of arrival (Δt) of the AE signals to the antenna array transducers [5-8]. It should be noted that the standard algorithm does not consider the anisotropy of acoustic properties of the test objects and the dispersion properties of the registered AE signals. The acoustic properties anisotropy results in the dependence between V parameter and the direction of AE signal propagation. During the acoustic wave propagation, the nonlinear changes of signal frequency characteristics occur in the dispersion medium, which is accompanied by high-frequency modes attenuation in the AE source near zone. This physical phenomenon results in tailing of the leading edge of the recorded AE signals and the increase of the time parameter Δt. Therefore, the joint effect of acoustic properties anisotropy and dispersion produces significant impact on the values of Δt and V parameters, used for calculation of AE sources coordinates. Figure 1 presents the diagram of determination of AE source coordinate at linear location.
Figure 1. Diagram of determination of AE source coordinate using standard linear location algorithm.

The standard linear location algorithm is based on calculating the coordinates \((R_1 \text{ and } R_2)\) of the AE source from the time difference of arrival of the AE signals to the antenna array transducers \((\Delta t = t_1 - t_2)\) and its propagation velocity \(V\). The AE source coordinates are calculated as follows:

\[
\begin{align*}
    t_1 &= \frac{R_1}{V} \\
    t_2 &= \frac{R_2}{V} \\
    t_1 - t_2 &= \Delta t \\
    R_1 &= \frac{L - V \cdot \Delta t}{2}
\end{align*}
\]  

(1) 

(2)

2. Materials and equipment

To determine the accuracy of the AE sources coordinates using the standard linear location algorithm, laboratory tests on the static tension of a steel sample to destruction have been performed. The figure 2 presents the general view of testing the sample at electromechanical testing system Instron-5982.

Figure 2. The sample (1), installed in the grips (2 and 3) of electromechanical testing system Instron-5982 with the transducers VS 150-RIC (4) fixed with the clamps (5).

During the sample testing, the load was automatically increased at the rate of the testing system active traverse displacement of 1 mm·min\(^{-1}\). The overall dimensions of the tested samples were 500x40x4 mm. Two holes 5 mm in diameter were drilled as stress concentrators at a distance of 110 mm from the end surfaces of the sample. The resonant acoustic emission transducers (AET) of VS 150-RIC were installed at the distance of 40 mm from the concentrators so that the linear location size was \(L = 360\) mm. Before loading the steel sample, the measurement devices were adjusted. The acoustic signal recording was performed using four-channel AE measurement system Vallen AMSY-6. The AE signal discrimination threshold was selected equal to \(u_{th} = 44\) dB, digital filter band pass
corresponded to frequency range $\Delta f = 100$-850 kHz. To determine the AE signal propagation velocity, the standard calculation method described in the regulatory document PB 03-593-03 was used. The group velocity value determined using Su-Nielsen source (0.3 mm clutch pencil lead fracture) constituted $V_g = 4500$ m s$^{-1}$ at the level of AE signals maximal amplitude $u_m = 94$-96 dB.

3. Results and discussion
Synchronously with Ae monitoring, the video camera EOS 60D recorded the process of material deformation in the concentrators area. In the process of loading the samples, some asymmetry in the degree of damages accumulation was observed in the concentrators area and, correspondingly, the asymmetry of the loading processes in the areas of location of upper and lower hole which correspondingly impacted on the AE events accumulation diagrams recorded by the acoustic emission systems. The earlier development of the main cracks accompanied by the loss of the bearing capacity and the sample destruction also took place in one of the concentrators. Figure 3 presents the pattern of material deformation and the sample destruction.

![Figure 3. The pattern of deformation and destruction of the steel sample of grade St3.](image)

Figure 3 shows the areas of concentrators where the most intensive local material structure destructions took place. It is known, that the maximal density of AE events is to be registered at the area of the sample material destruction. However, as we can see from the experiments conducted, in the event of presence of stress concentrators in the near zone of the receiving transducers (at the distance of 40 mm from the holes), the maximal AE events density recorded by Vallen AMSY-6 system, shifted correspondingly by 70 mm from the center of the holes. The diagrams of figure 4 present the change dynamics of locational signals maximal amplitude (a) and the coordinate location of AE events (b), recorded in the course of AE diagnostics of the steel sample during tension.

![Figure 4. The change dynamics of locational signals maximal amplitude (a) and the coordinate location of AE events (b), recorded in the process steel sample testing.](image)
As follows from the figure 4 (a), the arrays of locational signals with the maximal amplitude of 44 to 97 dB were registered in the process of AE testing. At the period from 85th to 400th second of AE monitoring, the maximal level of the registered signal amplitude reached 97 dB. The maximum of AE events distribution was registered at the area of #1 AET installation, and the sample destruction occurred in the hole area at the distance of 40 mm from it. According to the linear location results, presented in figure 4 (b), the maximum density of AE events, reaching 39 units mm\(^{-1}\), was observed at the coordinate \(x_{max} = 40\) mm, which corresponds to the absolute error \(\Delta = |x_{max} - x_i| = |40 - 110| = 70\) mm, where \(x_i\) is the true coordinate of the destruction place. A specific feature of the standard location algorithm application is the use of the group velocity value \(V_g = 4500\) m s\(^{-1}\) determined for Su-Nielsen source with the maximal amplitude level \(u_m = 94\) to 96 dB, while the amplitude of the main array of the recorded location signals was in the range of \(u_m = 45\) to 65 dB. Therefore, the use of the standard method for locating AE sources oriented to the signal amplitude level from a Su-Nielsen source results in significant errors in determination the coordinates of AE sources located in AET near zone, as follows from figure 4 (b).

To assess the impact of the acoustic signals dispersion properties on the value of the group velocity of AE signal propagation \(V_g\), the additional experimental studies have been performed. In this case, the AE signals were generated using the electronic simulator “Interunis” with the connected broadband transducer UT-1000, situated outside the location area at the distance of 40 mm from # 1 AET. During the testing of the group velocity \(V_g\), the electronic simulator voltage was selected so that to change the maximal amplitude of the recorded signals \((u_m)\) in the range from 55 to 100 dB in 5 dB steps. Based on the results of the studies performed, figure 5 shows the dependence of the change in the group velocity of AE signals propagation from the level of the maximal source amplitude \((u_m)\).

![Figure 5](image)

Figure 5. The dependence of the velocity of AE signals propagation on the acoustic signals source amplitude.

As we can see from figure 5, the value of the AE signals propagation velocity largely depends on the maximum amplitude of the recorded signals. The use of the Su-Nielsen source makes it possible to generate 90-95 dB AE signals. The average propagation velocity of such signals corresponds to \(V_g = 4500\) m s\(^{-1}\). When using an electronic simulator, it is possible to change the values of the AE signals amplitude within a wide range. For example, for 55 dB signals, the TDA value was equal to \(\Delta t = 122\) µs, which corresponds to \(V_g = L/\Delta t = 360 \cdot 10^{-3} / (122 \cdot 10^{-6}) = 2950\) m s\(^{-1}\). In this case, for 65 dB signals, the velocity value reached as much as 3800 m s\(^{-1}\). Therefore, even the minor changes in the AE signals amplitude result in significant scatter of \(V_g\) values, and subsequently, to linear location building error. The greatest effect of the nonlinearity of \(V_g(u_m)\) diagram and the dispersion properties of acoustic signals is observed when the AE source is located in the near zone of one of the antenna array transducers at a distance of \(R_i \leq 100\) mm. Depending on the recorded signals amplitude, the absolute error level can exceed the true AE source position by more than 1.5 times.
As is seen from figure 6, in the process of the steel sample loading 5553 AE signals of the amplitude below 60 dB was registered in the destruction area, which corresponds to 75% of the total number of the located signals. According to the results presented in figure 5, the maximal velocity of propagation of AE signals of the amplitude below 60 dB does not exceed $V_g = 3300 \text{ m/s}$. The average velocity value for high-amplitude signals corresponds to $V_g = 4500 \text{ m/s}$. Such $V_g$ values changes are due to the effect of the dispersion properties and the threshold AE signals discrimination algorithm in the time parameter value $\Delta t$. As follows from the publications [4, 5], the threshold registration of AE signals characterized with the oscillating front edge form, results in temporary delay and the TDA increase by the permanent value $\Delta t_a$, correlating with the additive error component. The temporary delay is due to the fact that at the initial period of the signal distribution, the main energy of the wave packet is born by the high-frequency components possessing the highest value of the propagation velocity. As the AE source moves off from the transducers, the high-frequency modes quickly attenuate which reduces the TDA measurement error. The change of the frequency characteristics in the process of acoustic signals attenuation significantly impacts the AE signals propagation velocity. The reduction of the AE signal maximal amplitude results in the reduction of the energy of high-frequency components of the spectrum, and, therefore, the increase of $\Delta t$ measurement error. Therefore, the effect of AE signals dispersion properties results in multiplicative error of TDA measurement. The above-listed factors significantly affect the accuracy of AE events location in the transducer near zone. For numerical estimation of additive and multiplicative error components, figure 7 shows the distribution of $\Delta t$ values of AE events, registered in the #1 AET near zone at the distance of ±40 mm from the center of the holes where the sample destruction took place.
Figure 7 shows the distribution of the values of the temporal parameter Δτ of AE events recorded by the antenna array transducers in the steel sample destruction area. Due to the fact that the destruction area is located at a distance of 40 mm from #1 AET and 320 mm from #2 AET, t₁ < t₂ and Δτ = t₁ − t₂ < 0. The maximum of TDA distribution corresponds to the value of Δτₘ = -115 μs. To determine the additive error component, the TDA parameter was calculated according to the standard algorithm Δτₛ = \frac{2 \times (t₂ − t₁) − L}{Vₐ} = \frac{2 \times (110 − 70) − 360}{4.5} = -62.2 μs. Therefore, the additive component of TDA measurement error was Δₐ = |Δτₘ − Δτₛ| = |−115 + 62.2| = 52.8 μs. For numerical estimation the multiplicative error, the average scatter of Δτ values was calculated relative to the TDA maximum distribution coordinate, depending on the number of recorded AE events at the distance of ± 40 mm from the center of destruction (hole): γ(Nₑ) = Δγ/Δτₑ, where Nₑ is the total number of registered AE events. For Δτ = -115 μs, the deviation from Δτₑ corresponds to Δγ = 0 μs, which means that the multiplicative error component is equal to zero. For example, for Δτ = -135 μs, the TDA values deviation corresponds to Δγ = Δτₑ = |-135+115| = 20 μs, and the multiplicative error is γ(Nₑ) = 20/(439/16407) = 0.535. Based on the statistical processing of the data presented in figure 7, it was determined the average value of the multiplicative error, equal to γ(Nₑ) = 0.67, indicating the average deviation of the TDA values by 67% relative to the median of Δτ distribution.

4. Conclusions
The effect of the additive and multiplicative error components on the accuracy of the linear location of AE sources located in the near zone at a distance of 40 mm from AET has been studied. To assess the coordinate location accuracy, calculated by the standard algorithm, a tensile test of a steel sample with stress concentrators in the form of holes was performed. According to the studies, when the standard algorithm is used, the absolute error in the coordinate location of AE events, that occurs when the source is located in the AET near zone, can differ from the true position by 1.5 times. Based on the studies performed, the dependence between the group velocity of AE signal propagation and its amplitude was recorded. A numerical estimation of the effect of the additive and multiplicative error components on determination of TDA parameter on the coordinate location accuracy was performed. To improve the accuracy of determining the coordinate location of AE events, it is necessary to take into account the dependence of the wave packet propagation velocity on the signal amplitude, as well as the effect of the additive and multiplicative error components in determining the TDA.

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