ACOUSTIC EMISSION FROM IMPACTS OF RIGID BODIES

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Abstract

The characteristics of stress waves accompanying the collisions of rigid bodies are investigated. It is shown that high-frequency transducer of acoustic emission apparatus transforms initial impact perturbation into two separate signals, arriving with delay equal to impact duration. AE signals are generated at the moments corresponding to discontinuities of the derivative of surface displacement function of impacting bodies; i.e., at the initial moment of loading and the final moment of contact. It is shown experimentally that different Lamb modes recorded in the far-field zone of the impact source contain double signals arriving with the same delay as the signals in the near-field zone. The relationship between the AE waveform and the impact parameters determined in the study enables one to estimate physical characteristics of impact, such as surface displacement, contact time and impact force. Practical significance of these findings for evaluation of structural integrity is discussed.

Keywords: Impact waveform, Contact duration, Double AE signals, Wave dispersion

Introduction

Stress waves excited by impacts of rigid bodies are studied in different applications of acoustic nondestructive testing. In the practice of AE testing the impacts are considered mechanical interferences, which have to be filtered from “useful” signals related to fracture process. However, since an impact itself presents a danger to the structural integrity, the relationship between the mechanical characteristics and AE parameters of impacts may be used for estimation of the impact hazard. The latter consideration, particularly, served as a basis for designing a loose-part monitoring nondestructive method, which is used widely in nuclear reactor industry; see [1].

To study the mechanical parameters of colliding bodies and stress distribution in the contact zone the analysis known as Hertz theory of impact are generally applied. The theory was based on assumption of absolutely elastic collision. For spheroidal surfaces, the force-deformation relation needed to estimate the duration of impact and the maximum indentation was obtained using Hertz calculations. Johnson [2] and Goldsmith [3] covered the theory in detail.

However, most impacts are not fully elastic. Impact energy loss may incorporate different forms of dissipation such as viscoelastic work performed on the materials of the impacting bodies, plastic deformation of contact surfaces and emission of stress wave in the bodies. To analyze an inelastic stage of impact loading a rigid-perfectly-plastic material model is commonly used. It assumes that the elastic deformation is small enough to be negligible and the material flows plastically. For sphere-sphere contact, Johnson [2] shows that, under those assumptions, yield is initiated when the mean contact pressure is $1.1Y$ and the flow becomes fully plastic at about $3Y$, where $Y$ is the yield stress. He gives the ranges of initial velocities of colliding bodies for preliminary estimation of impact regime.
A phenomenon of stress wave generation occurring at impact is an important aspect of a dynamic contact mechanics focused in many studies. The wave approach was applied by Goldsmith to many problems [3] and also covered by Zukas et al. [4]. Tsai [2] got a theoretical solution of wave motion in elastic half-space by combining Hertz theory of impact with a Lamb wave theory. The results were obtained on assumption that stress wave effects account for a small fraction of impact energy and do not influence the local deformation significantly.

Proctor and Breckenridge [5] conducted AE analyses of elastic sphere collisions with a thick plate. They showed that when a Green’s transfer function and an impulse response of receiving transducer are known, a dynamic force of acoustic source may be obtained using a transducer response function. Their numerical results agree with theoretical calculations.

Ono et al. [6] studied the impact damage of CFRP plates using AE monitoring and surface evaluation. The force-indentation was obtained experimentally. Authors distinguished two classes of AE signals: impact related and matrix fracture related. Their study demonstrated the capabilities of AE method for diagnostics of impact failure processes in composite materials.

The idea of this paper was to determine the most informative and persistent AE waveform parameters of impact and to attempt evaluating the impact hazard. To this end, an investigation of collisions of different bodies on thick metallic plates at various distances from the source location was conducted and numerical analysis of normal impacts of sphere was carried out. The influence of the frequency range of the receiving equipment on the output signals calculated at modeling was studied.

**Impact properties.**

Derived on the basis of the Hertz law, a solution for the maximum indentation \( h_m \) and contact time \( T \) of elastic impact of a sphere on a smooth surface of rigid massive plate is given by Landau and Lifshitz [7]:

\[
h_m = \left( \frac{15}{16} m v_0^2 (x_1 + x_2) R^{-0.5} \right)^{0.4},
\]

where

\[
x_t = \frac{(1 - v_t^2)}{E_t}.
\]

\[
T = 2.9432 \cdot \frac{15}{16} \left( x_1 + x_2 \right) \left( m v_0^{-0.2} R^{-0.2} \right)^{0.4}.
\]

Here, \( h_m \) is maximum displacement of the bodies; i.e., total of deformation of both surfaces, \( v_0 \) is a sphere velocity at a moment of collision, \( R \) is a sphere radius, \( m \) is a sphere mass, \( E_{t(2)} \) and \( v_{t(2)} \) are Young’s modulus and Poisson’s ratio for the plate (or sphere), respectively. The formula was obtained on the assumption that \( m << M \), where \( M \) is a plate mass.

A force-indentation relationship for sphere-to-sphere contact was given by Johnson in a power form [2]:

\[
F = k h_m^{3/2},
\]
where \( F \) is normal force pressing the solids together and \( k \) is a constant depending on the sphere radius and elastic properties of the sphere materials.

Landau [7] and Johnson [2] show that the latter formula is also valid for any 3D non-conformal contact of solids, under the condition that the contact area must remain small compared to the bodies’ dimensions. Since these requirements are met for sphere to plate contact, we may apply this relationship to force estimation.

Deresiewicz [8] first derived a temporal dependence of surface displacement at the top point of a sphere in a form of a half-sine function, describing the dependence with high precision:

\[
\frac{h(t)}{h_m} = \sin(\frac{\pi t}{T})
\]  

(4)

Frequency range of impact perturbation may be estimated in a standard way given by Harkevich [9] on assumption that the main impact energy lies in the range between zero and the frequency value, at which the spectrum \( S_\omega \) of the displacement function vanishes for the first time. Fourier transform of a half-sine is calculated by the formula:

\[
S_\omega = \frac{2h_m T}{\pi} \frac{\cos(\omega T/2)}{1 - \left(\frac{2 \omega T/2}{\pi}\right)^2}
\]

(5a)

This function gives a first zero at \( \omega T = \frac{3}{2} \pi \), from which we obtain the desired frequency range:

\[
\Delta f = \frac{3}{2T}
\]

(5b)

As expected, the frequency range and the contact time are related inversely, meaning the shorter is a contact time; i.e., the less is a mass and the higher is a velocity of a body, the broader is an impact spectrum.

However, the physical variable \( h(t) \), is not a stress wave itself. According to Aki and Richards [10] waves are generated at moments corresponding to discontinuities of the perturbation function. The lower is the order and the higher is the value of the discontinuity, the higher is the amplitude of the wave front; i.e., the amplitude of AE signal. While the surface deformation \( h(t) \) is a continuous function, its first derivative, which is a displacement velocity has two ordinary discontinuities at the initial and the final moments of the impact contact time. Besides, the high frequency tract is known to be more sensitive to derivative of the function, than to the function itself \(^1\). It means that impact should produce two high frequency wave fronts, arriving with delay equal to the contact period.

Difference of function derivative limits in the points of discontinuity gives the velocity jump value (discontinuity value) in a form of

\[
\Delta v = \pm \pi h_m / T
\]

(6a)

\(^1\) If a complex spectrum of function \( f(t) \) is \( S(\omega) \), then a spectrum of derivative of this function is \( j \omega S(\omega) \). This implies that while the signal response at low frequencies is determined mainly by the function itself, \( f(t) \), at high frequencies the influence of the term related to derivative of the function becomes predominant.
where plus sign refers to the first point and minus sign to the second one. Hence, the following relation between the jump value and the signal amplitude:

\[ A \propto \frac{\pi h_m}{T} \]  

(6b)

![Graphs showing signal analysis](image)

Fig. 1. Modeling of a high-frequency impact response a) system pulse characteristic. b) half-sine input function, h(t). c) the convolution of a) and b). d) the resulting high-frequency output signal.

### Output AE Signals Analysis

To analyze the AE waveforms from impacts, a numerical modeling of collisions of a metal sphere (R = 11 mm) dropped upon a thick aluminum alloy plate from the height of 300 mm with a zero initial velocity was carried out. High-frequency Butterworth digital filter and PAC R50I transducer response were used in the modeling.

An input source function, h(t), given in Fig. 1b was calculated using Equations (1-4) in a form of half-sine. A response of the plate - transducer - apparatus system on Hsu-Nielsen pencil-lead break, presented in Fig. 1a, is assumed to be a pulse characteristic of the system, p_{sys}(t).

A convolution of the pulse characteristic of the system and the input source function \( s(t) = h(t) * p_{sys}(t) \), given in Fig. 1c demonstrates the presence of low frequency components,
Fig. 2. Modeling of a high-frequency AE crack movement response. (a) The scheme of a slow crack movement function; (b) a modeled output waveform consisting of three signals, which are separated by time delays corresponding to the break points of the function. (c) The scheme of a rapid crack movement function; (d) a modeled output waveform consisting of overlapping signals; (e, f) the dependence of output signal amplitude on a value of the function derivative jump.

which should be removed from the final high-frequency output signal. To this end, the convolution, $s(t)$, was filtered by a high-pass 5-th order Butterworth filter with a cutoff frequency of 50
kHz. The result of filtration is shown in Fig. 1d, where one can easily distinguish two separate signals coming with a delay equal to the impact duration.

Our analysis shows that a pair of signals occurs when the cutoff frequency of a high-pass filter has the same order as the highest frequency of impact, determined from Eq. (5b). If the impact duration and the sensor decay constant, τ, satisfy the condition of $T \gg \tau$, the signals do not overlap and are separated in a time domain by a delay equal to impact duration.

Basically the same considerations may be used in the analysis of arbitrary AE source, e.g., cracking. Let’s assume the crack movement function is determined by a broken line function like that given in Fig. 2a. Then a deformation/stress jump will occur at three break points, which are the beginning of crack extension, maximum and crack propagation arrest. The output signals modeled by the convolution of input function and a high-frequency AE transducer response (with range from 50 kHz to 200 kHz) are shown in Fig. 2b. Each of three signals presented in this figure occurs in the corresponding breakpoint of the crack movement function. They are well distinguished because the intervals between the discontinuity points exceed the decay period. On the contrary, signals in Fig. 2d overlap and are not separated. Finally, Figs. 2(e, f) illustrate the dependence of an output signal amplitude on the value of the derivative jump (velocity jump), which in turn is determined by the line slopes.

**Experimental Setup and Results**

The experimental part of the study included three types of experiments, which are normal collisions of metallic spheres dropped upon an upper surface of thick duralumin plate; grazing collisions of spheres against a vertical steel plate; and impacts of a metal screwdriver.

Recording system used in the study was a PAC 4-channel DiSP AE system, with R50I and R15I sensors, produced by Physical Acoustic Corp., USA. Signals were filtered by analog band-pass filter of 10 - 1000 kHz, digitized at a sampling rate of 2 MHz, and recorded as 2048-point waveforms.

**Normal impacts of metal spheres**

The collisions of steel spheres dropped upon the plate surface from three different heights ($H = 0.1 \text{ m, 0.2 m and 0.3 m}$) with a zero initial velocity served as AE sources. Recoil heights were registered for impact energy loss analysis. Four different sizes of spheres were used, with radius ranging from 2.5 mm to 11 mm. Experimental setup consisted of a horizontal aluminum alloy plate having size $300 \times 495 \times 95 \text{ mm}^3$, DiSP system and R50I AE transducer mounted on the same surface with the sphere impact location at the distance of 20 mm from the source.

The data given in Table 1 were obtained at a height of falling $H = 0.3 \text{ m}$ and include both geometrical and mechanical parameters of the spheres and the corresponding characteristics of impacts, such as contact time, maximum impact surface displacement and highest frequency calculated in accordance with Eqs. (1-3).

The initial velocities of the spheres at impacts calculated as $v = \sqrt{2gH}$ were equal to 2.42 m/s, where $g$ is acceleration of gravity. Note that the same velocity value is given by Eq. (6a).
Fig. 3. (a) Hsu-Nielsen pencil-lead break related waveform; (b-e) AE signals registered from impacts of different size spheres (with the radius of 2.5, 3.5, 8 and 11 mm) dropped on the aluminium plate. Arrow #1 points to the first waveform peak related to impact loading; arrow #2 points to the secondary peak related to unloading of the plate.
Table 1 Mechanical parameters of dropping spheres and impacts.

<table>
<thead>
<tr>
<th>Sphere radius, R, mm</th>
<th>Sphere mass, m, g</th>
<th>Maximum indentation, h_m (calc), mm</th>
<th>Impact duration, T (calc), µs</th>
<th>Impact frequency, F (calc), kHz</th>
<th>Impact duration, &lt;T&gt; (exp), µs</th>
<th>Standard deviation, σ, (exp), µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>43.49</td>
<td>0.069</td>
<td>84</td>
<td>17.9</td>
<td>82.8</td>
<td>1.03</td>
</tr>
<tr>
<td>8</td>
<td>16.73</td>
<td>0.050</td>
<td>61.1</td>
<td>24.5</td>
<td>61.4</td>
<td>0.4</td>
</tr>
<tr>
<td>3.5</td>
<td>1.40</td>
<td>0.022</td>
<td>26.7</td>
<td>56</td>
<td>28.4</td>
<td>0.9</td>
</tr>
<tr>
<td>2.5</td>
<td>0.51</td>
<td>0.016</td>
<td>19.1</td>
<td>78.5</td>
<td>21.7</td>
<td>0.85</td>
</tr>
</tbody>
</table>

A restitution coefficient, e, which is a measure of an energy loss during impact was estimated as a quotient \( e = \frac{v_f}{v_i} \), where \( v_i \) and \( v_f \) are velocities before and after impact, respectively. The coefficient changed from 0.61 for the large sphere (\( R = 11 \) mm) to 0.7 for the small one (\( R = 2.5 \) mm) indicating the presence of energy dissipation during the impact experiments. Dissipation mechanisms observed are both plastic deformation of the plate and wave emission, which is confirmed by the presence of shallow indentations at the surface of the plate remaining after the collisions and a stress wave emission during impacts.

The examples of typical impact waveforms recorded for each sphere size are given in Figs. 3(b – e). For more comprehensive analysis a Hsu-Nielsen pencil-lead break response, which is considered as an impulse response of the whole system (plate – transducer - AE apparatus) at a distance of 20 mm from the source is plotted in Fig. 3a.

It follows from Fig. 3a that if a short step-pulse is imposed at \( t = 0 \) µs, a peak signal amplitude appears at a moment of \( t \sim 7.4 \) µs (arrow #1). Similar patterns may be seen in Figs. 3(b - e), where first peaks occur at the same moments from the beginning of the waveforms.

![Amplitude – Velocity dependence obtained experimentally for three sphere sizes each dropped from three different heights: 0.1 m, 0.2 m and 0.3 m.](image)

Fig. 4. Amplitude – Velocity dependence obtained experimentally for three sphere sizes each dropped from three different heights: 0.1 m, 0.2 m and 0.3 m.

Values of first peak amplitudes measured in experiments amounted to ~ 2 mV (86 dB) for all spheres. The independence of AE amplitudes from the sphere size may serve as experimental validation of the statement (see Eq. 6b) that at high frequencies the first peak amplitude corresponds to the initial loading velocity. The latter in all experiments was determined by the same
dropping height of 0.3 m and was equal to \( \sim 2.42 \) m/s. This conclusion is also confirmed by the correlation between the velocities obtained for three different heights of dropping spheres and the corresponding loading related amplitudes of the AE waveforms. Amplitude (A)-Velocity (V) relationship shown in Fig. 4 is fitted by a linear function \( A = 1.1V - 0.38 \) with the correlation coefficient \( R_c = 0.85 \). Note that the obtained coefficients of the linear function are valid only for the given plate.

In addition to loading related peaks, secondary peaks marked by arrow #2 may be also observed in Figs. 3(b - e). These peaks relate to unloading of the plate and are separated from the loading-related peaks by the delays equal to impact duration. The delay values obtained in more than 10 impacts for every sphere size agree well with the calculated durations of impacts; average durations measured as signal delays and their standard deviations are given in the last columns of the Table 1.

The measured amplitudes of the secondary peaks exceed those of the first peaks and rise from 2.8 mV (89 dB) for the small sphere to 8 mV (98 dB) for the large one, implying the unloading displacement velocity exceeds the initial loading velocity. Seeming contradiction between the decrease of recoil velocity and the increase of unloading velocity estimated by AE amplitudes may be explained by the fact that velocity is a vector quantity, depending on impact regime. Thus, at the beginning of loading the impact contact is determined by a normal impulse component only; at the stage of plastic deformation tangential components occur as well. A change in velocity component orientation leads to the reduction of the algebraic value of the velocity, and hence to the decrease of recoil height. The ratio of tangential to normal impulse components was first introduced by Brach [11] for treating oblique impact problems.

Taking into account that the impacts observed are not fully elastic, we may infer that the temporal indentation dependence here can be described by a symmetrical half-sine only during the elastic stage of loading, with the parameters of the function calculated from equations (1-4). Since the unloading velocity determined by a second peak amplitude, 1.5-3 times higher than at initial stage, the penetration maximum should shift to the right on the time axis, and due to the material hardening its value should be less than that calculated for a case of elastic impact, \( h_m \). This reveals some perspectives of AE verification of impact models and estimation of impact hazard. In particular, the above conclusions based on AE data agree with calculations of temporal dependence of the contact area carried out by Johnson [2] for modeling of a purely viscous material behavior under the action of a sinusoidal varying force.

Also, the obtained relationships between the AE features and the mechanical parameters allow one to estimate quantitatively the loading and the unloading velocities, impact duration and maximum penetration (estimated for elastic impact). A velocity ratio obtained as \( A_{\text{unld}}/A_{\text{ld}} \), where \( A_{\text{unld}} \) and \( A_{\text{ld}} \) are the unloading/loading related amplitudes of impact waveform, respectively, may serve as an acoustic measure of energy loss. The higher is the velocity ratio, the greater is the viscoelastic work performed on the materials of the impacting bodies, and therefore the larger is a size of a plastic zone occurring below the contact surface.

Besides, the value of \( A_{\text{ld}} \) corresponding to impact velocity, may be used together with the non-dimensional parameter \( (\rho V^2/Y_d) \) obtained by Johnson for preliminary estimate of impact regime. Here \( Y_d \) is dynamic yield strength. The following table from [2] gives the impact regimes as a function of this parameter and initial velocity:
According to this table and taking into consideration that the initial velocities of the spheres were about 2.42 m/sec, we can conclude that in all cases an elasto-plastic regime of impacts was observed.

It is important that regardless of the fact that the collisions were not fully elastic, the obtained experimental values of impact durations show a good agreement with the theory. Similar results were obtained by Gugan [12], who demonstrated that the measurements on a croquet-ball contact time are well described by Hertz theory, even when about 40% of the kinetic energy is lost on collision.

Finally, note that the emission of stress waves occurs during the entire period of impact duration and over the whole contact area, which in our case is a circle of a variable radius. More specifically, these factors should be considered for the calculation of the displacement function. However, when a displacement velocity is measured by a high-frequency sensor, the output AE signal is determined mainly by the strongest discontinuity of the function, while the contribution of the other components may be neglected. The strongest displacement discontinuity here occurs at the top point of a dropping sphere at the two characteristic moments of contact. This is the reason why the observed delays between the pairs of loading-unloading related signals correlate well with the impact durations calculated using equation (2).

Analysis of impact waveforms in the presence of wave dispersion.

Investigation of tangential impact waveforms was conducted on a vertical steel plate having a size of 2000 x 1000 x 100 mm$^3$. Steel sphere (R = 8 mm) fixed on a 0.3-m long thread was dropped with a zero initial velocity upon the plate side, and two R151 sensors were mounted on the same side of the plate at distances of 20 mm and 920 mm from impact source. Waveform recording in both channels was triggered by the first arriving signal.

Estimation of a wavelength at a frequency of 150 kHz and shear wave velocity of 3.2 km/s gives a value of 21 mm, which means that the neighboring sensor is located in the near-field zone, while the remote one – in the far-field zone. The wavelength and the plate thickness (100 mm) proportion indicate a presence of acoustic dispersion thus complicating interpretation of wave pattern. To simplify the waveform analysis we first used a pencil-lead break as an acoustic source, producing a step displacement source function. AE signals from this source recorded by the neighboring and the remote channels are shown in Figs. 5a and 5b, correspondingly. The first signal looks rather compact because all harmonics are in phase near the source. On the contrary, the second signal occurs to be compound and diffused due to the dispersion. To interpret the obtained wave pattern we used a classic spectral approach and a group velocity concept. Such approach is possible due to the spatial spectral decomposition of initial perturbation occurring in a dispersive medium. Under these conditions a group velocity, which is a propagation velocity of neighboring harmonics envelope, may be used for analysis of signal envelope peaks.

This analysis allows us to interpret waveforms, to analyze arrival times corresponding to different peaks, and to calculate peak delays, peak velocities and wave propagation distance. Algorithm of the procedure can be easily realized and embedded into the standard software.
Fig. 5. AE signals from Hsu-Nielsen source. (a) at a distance of 20 mm from sensor; (b) at a distance of 920 mm from sensor.

Thus, the first step of data processing includes calculation of signal envelope, determination of peak arrival times and peak widths, i.e., peak segments and carrier spectrums of these segments. Next, group velocities, corresponding to the dominant frequency of the carrier spectrum are calculated. The results of the processing are shown in Fig. 6, where our considerations are limited to four main waveform peaks marked by the corresponding numerals. Carrier segment belonging to the first peak of the envelope and the corresponding spectrum with a resonance at 130 kHz are given in Figs. 6a and 6b, respectively.

Dispersion analysis (made using a special PAC software PLOTRLQ) allows us to conclude that the first envelope maximum is formed mainly by symmetric (S) and anti-symmetric (A) 0-th-order Lamb modes: $A_{10}$, $S_{00}$, $A_{30}$ (here small $l$ and $s$ mean longitudinal and transverse modes, correspondingly). As follows from Fig. 7, at 130 kHz, these modes converge to the point of 3.13 km/s, which determines the group velocity of the first waveform peak. The obtained value shows good agreement with the velocity calculated from delta-T, $\Delta t$ = 287 $\mu$s, and the propagation distance, $\Delta L$ = 900 mm: $c = \Delta L/\Delta t = 3.136$ km/s.

The second peak formation may be interpreted similarly. For the dominant carrier frequency equal to 114 kHz, modes come together at the velocity of 2.56 km/s; see Fig. 8. As follows from this figure the second peak is formed mainly by the first-order Lamb modes: $S_{11}$, $A_{31}$, $S_{11}$. The point where the modes converge is circled. The obtained velocity value agrees with the one computed from delta-T from delta-T, $\Delta t$ = 352 $\mu$s, and the propagation distance, $L$ = 900 mm: $c = L/\Delta t = 2.556$ km/s. The parameters of the other waveform peaks, obtained in the similar way, are the following: the third maximum has a dominant frequency of 99 kHz, propagating at the velocity of 2.31 km/s; the forth at the frequency of 72 kHz, propagating at the velocity of 1.62 km/s.
Fig. 6. AE signal at the remote sensor: (a) signal envelope with the carrier of the first peak; (b) Spectrum of the first peak carrier.

Fig. 7. Zeroth-order Lamb modes forming the first peak of AE signal envelope at a distance of 920 mm from the source. The point where the modes converge is circled.

The advantage of the considered classic time-spectrum approach is that it provides a convenient physically based tool of AE data processing and gives a physical interpretation to wave pattern obtained at AE testing. Besides, it may be applied for estimation of wave propagation distance to improve source location results. The location formula, using characteristics of a single waveform is the following:
Fig. 8. First-order Lamb modes forming the second peak of AE signal envelope at a distance of 920 mm from the source. The point where the modes converge is circled.

\[ R = \frac{\Delta t c_i c_2}{(c_2 - c_1)}. \]  

Here R is a distance from a sensor to a source, \( c_i \), where \( i = 1, 2, \ldots \), velocity of i-th peak of the waveform envelope; \( \Delta t \) is the delay between two peaks. Note that the distance may be calculated using different combinations of several peaks. Also note that for a given method of distance estimation, precise determination of wave arrival does not play any role, which is important in a case of low signal-to-noise ratio.

Following the same way of AE wave pattern interpretation we can analyze a tangent impact of a steel sphere against the vertical plate. As in previous case, the sensors were mounted at a distance of 20 mm and 920 mm from the source. Impact waveforms shown in Fig. 9a reveal two distinct signals coming at a delay of 54 \( \mu s \). Though the contact time was not calculated, the characteristic features of the waveforms obtained affirm that the delay corresponds to the contact time, which was 7 \( \mu s \) less than at normal impact. A group of double signal pairs recorded by the remote channel is shown in Fig. 9b. Signal numbering corresponds to that obtained at the pencil-lead break, while stroke denotes the repeating disturbance. Double signal delays exactly correspond to the delay obtained at the near sensor, which confirms the presence of double disturbances in different Lamb modes. The absence of peaks denoted as 2 and 2' relates to the overlapping of 1'-2 and 2'-3 disturbances.
Fig. 9. AE waveforms from impact of 8-mm steel sphere recorded in near-field and far-field zones by R15I sensors. (a) Repeated signals registered by R15I sensor mounted on the surface of thick steel plate near the source location. (b) Series of repeated signals registered by R15I sensor at the distance of 920 mm from the impact source.

Fig. 10. AE waveforms from impact of metal screwdriver recorded in near and far zones by R15I sensors. (a) Repeated signals registered by R15I sensor mounted on the surface of thick steel plate near the source location. (b) Series of repeated signals registered by R15I sensor at the distance of 920 mm from the impact source.
Finally, a wave pattern obtained from the impact of an 80-mm length metal screwdriver on the vertical steel plate was analyzed. Typical impact waveforms captured by near-field (20 mm) and remote-field (920 mm) sensors are shown in Figs. 10a and 10b, correspondingly. At interpretation of Fig. 10a, it is easy to suppose that the repeating signal, denoted as 1’, relates to reverberation in long hammering object itself. However, such signal should arrive at a delay of ~50 µs, while the observed delay is equal to 298 µs. It means that like in previous cases, the only suitable explanation to double signal effect is that the second signal relates to the release of the plate after the impact and that the delay value corresponds to the impact duration. Figure 10b illustrates the presence of double signals in different Lamb modes recorded at the remote channel. From Figs. 9 and 10, it can be seen that the loading and the unloading amplitudes in both experiments were practically the same. It implies that the impacts of steel bodies against the steel plate were fully elastic.

Conclusions

1. High-frequency AE channel transforms input impact function into two separate signals related first, to loading and second, to unloading of bodies at impact. Signal delay correlates well with the impact duration.
2. A pair of signals is obtained when the lower cutoff frequency of the transmission channel is of the same order of the upper frequency of the impact.
3. Use of double signal effect allows one to estimate the contact time at collision of rigid bodies regardless of the elastic properties and geometry of the bodies, impact direction, etc.
4. An AE amplitude from the impact correlates with the jump in the velocity of the loading function, but not with the function itself. Together with delay-based measurements of impact duration, the A-V relationship allows one to estimate the maximum indentation and the impact force. The ratio of peak amplitudes provides a preliminary evaluation of an impact regime, and therefore, the danger of impact damage.
5. The presence of double signals from impacts is observed in different Lamb modes. Signal delays in far-field zone are equal to that measured in near-field zone.
6. Finally, the theoretical solution for impacts of metal spheres against thick plates allow considering such impacts as calibrated acoustic sources with known parameters along with a pencil-lead break, which is a widely used simulator of AE.

References