RELATION BETWEEN AMPLITUDE AND DURATION OF ACOUSTIC EMISSION SIGNALS

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ABSTRACT. The correlation between A and D in the AE signals coming from deformation tests in steel samples and explosion tests in Zry tubes is analysed. The graph for the logarithm of relative Amplitude versus Duration of AE signals is a band between two slightly convex lines. If each burst is a simple event a unique straight line is expected. Following a previous model of our Group, bursts were modelled as superposition of a number of events.

INTRODUCTION

As is usually known the Acoustic Emission bursts signals are asymmetric and are characterized by their Amplitude (A), Duration (D) and Risetime (R). In previous papers we studied different features of these parameters and the relations between them. In particular, the Log-normal distribution was obtained for the A parameter. The underlying physical meaning is that the detected AE signal, is the complex consequence of a great number of random independent sources, which individual effects are linked [1]. Moreover, we proved in [1, 2] that the sensor produced a linear relation between the incoming mechanical signal and the outgoing electrical signal, being its influence on Duration or Risetime much more complex. In this sense the sensor was modeled by a four-order differential equation in previous work [2, 3].

In the present paper we continue studying the relation between Amplitude and Duration in the AE signals coming from deformation tests in steel tube samples (MAN tests) and explosion tests in Zry tubes (ARI tests) [4, 5]. The graph for the logarithm of Amplitude versus Duration of experimental AE signals is a band between two slightly convex lines. In a previous paper, we developed a model consisting in the superposition of two signals: the original one and a signal originated as a reflection in a border of the sample [6].

An extension of the model was developed in this paper to better explain the A-D correlation, continuing published work on modelling AE signals and systems [1, 2, 6-11].
EXPERIMENTAL

In this paper we discuss the AE signals coming from deformation and crack propagation in samples from seamless tubes of steel and Zircaloy. Main AE sources are: dislocation movement, deformation, crack propagation and inclusion fracture.

Steel samples (MAN tests) [4] were rings obtained by transversal cut from tubes, with 14 cm external diameter, 1 cm thickness and 2 cm width. A section with a chord length of 6 cm was eliminated from each ring in order to introduce it in a device, which by opening introduced a distribution of stresses. Force was exerted by hand through a screw. A number of six samples were tested. In order to promote a local deformation and crack propagation; the test pieces were thinned out in the internal upper central region. The tubes are oxidized in their natural state. Three samples were treated without their oxide layer (MAN5, MAN6, MAN7) and in the others, this layer was not eliminated (MAN2, MAN3, MAN4). Therefore AE in the first three test pieces might proceed from steel deformation or crack propagation, but in the last three samples, crack of oxide layer is another possible source. Three AE transducers were allocated on each sample. Two of them acted as "guards" to eliminate the noise produced at the holding points. The third one, put on the top of the ring, where the maximum degree of deformation occurred, was a wide band sensor (300-800 kHz). The signals were immediately pre-amplified and then amplified and processed with the AE AEDOS system.

The analysis of the Acoustic Emission produced in Zry-4 CANDU fuel cladding (ARI tests) was also performed [5]. The tubes with closed ends were subject to a hydraulic experiment, during which the internal pressure was uniformly increased, at room temperature, until the tube broke by explosion. Two sets of samples were tested: five samples without any manufacture defects and other six samples with typical external surface defects. Electronic controlled hydraulic equipment used to pressurise the tube was specifically designed to reach the 600 atm necessary to explode the tubes. The dimensions of the tube were: 150 mm (length), 13 mm (external diameter) and 0.4 mm (wall thickness). An AE wide band sensor (300-800 kHz) was attached to the closing system. The signals were immediately pre-amplified and then amplified and processed with the AE AEDOS system. Pressure values were also recorded.

THE MODEL

In this paper we continue considering that an individual AE signal is a result of the convolution of the input mechanical pulse and the impulse response of the sensor, thought as a linear and time invariant system [1, 2]. When a mechanical pulse enters the sensor, the output is a negative exponential. The Risetime parameter is not considered here and we focus at complex signals that result from the superposition of individual ones. In our previous paper [6] we supposed that the form of each burst is:

\[ h(t) = A t^b e^{-\beta t} \sin(\omega t) u(t) \]  

being \( u(t) \) the step function, \( \beta \) the decay constant of the sensor, \( \omega \) the resonant frequency of the sensor, \( b \) a parameter connected with the Risetime, and \( A \) a parameter connected with the Amplitude. The enveloping \( e(t) \) is then:

\[ e(t) = A t^b e^{-\beta t} u(t) \]  

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In this paper, as in [6], we consider $b=0$, thus neglecting the Risetime and we also neglect the phase of signals, so from now on the signal will be:

$$y(t) = A e^{-\beta t} u(t)$$  \hspace{1cm} (3)

Until now a threshold zero value was considered. But if in such a signal, $A_U$ is the threshold used by the detection system, the relation between Amplitude and Duration is:

$$A_U = A e^{-\beta D} \quad \text{then} \quad \ln\left(\frac{A}{A_U}\right) = \beta D \quad \hspace{1cm} (4)$$

The Duration, $D$, is the time interval that is determined between the two extreme instants at which the signal crosses the threshold value set up in the detection system. If no superposition of signal occurs, the Logarithm of relative Amplitude and the Duration are proportional, both being related by the sensor decay constant $\beta$. If a second mechanical pulse arrives while the signal corresponding to the first is still operating, the apparent Duration of this complex signal augments. Then, for simple events (no superposition) roughly a linear relation between the Logarithm of relative Amplitude and Duration is expected.

The minimum complexity is obtained by adding two signals like Eqn. 3, the second one shifted and with different Amplitude:

$$y(t) = A_1 e^{-\beta t} + A_2 e^{-\beta (t-t_1)} \quad t > t_1. \quad \hspace{1cm} (5)$$

We suppose that the second signal is the replica of the first one, and comes from a reflection at a sample border. In this case, the Duration, $D$, is determined by the last time that the signal value takes the threshold amplitude value, $A_U$, that is to say:

$$A_U = A_1 e^{-\beta D} + A_2 e^{-\beta (D-t_1)} \quad \hspace{1cm} (6)$$

and in this case $A_1$ coincides with the maximum value of $y(t)$ in the $[0, D]$ time interval, which is the experimental measured Amplitude. Redistributing and applying logarithm:

$$z = \ln\left(\frac{A_1}{A_U}\right) = \beta D + \ln\left[1 - \frac{A_2}{A_U} e^{-\beta (D-t_1)}\right] \quad \hspace{1cm} (7)$$

The expression in Eqn.7 is not linear because of the second term. As it was demonstrated in [6], a convex curve is then expected for $z$ vs. $D$.

Continuing with this model, a superposition of more than two signals is considered in this paper and the following equation is obtained:

$$z = \ln\left(\frac{A_1}{A_U}\right) = \beta D + \ln\left[1 - \frac{A_2}{A_U} e^{-\beta (D-t_1)} - \frac{A_3}{A_U} e^{-\beta (D-t_2)} - \frac{A_4}{A_U} e^{-\beta (D-t_3)}\right] \quad \hspace{1cm} (8)$$
Some obvious considerations must be done about the Amplitudes and initial times \( A_3 < A_4 < A_5 \) and \( D > t_5 > t_4 > t_3 > t_2 \). Moreover, a more complex relation between Amplitudes and initial times were obtained when a positive argument of Logarithm was required. This problem was numerically solved.

RESULTS AND DISCUSSION

Table 1 shows the coefficients of the linear correlation matrix for Amplitude, Duration and Risetime. It can be observed that there exits an important correlation only for \( A \) and \( D \) parameters.

Figures 1 and 2 show experimental points as empty circles for typical MAN tests, for samples with and without oxide layer, respectively. Calculated points are different bold symbols: a right line corresponds to a unique signal \( z \) vs. \( D \) is a linear relation; bold squares are for superposition of two signals; bold circles are for superposition of three signals; bold triangles are for superposition of five signals. The same criteria were used in Figure 3 for a typical ARI test. All graphs were represented with the same scales.

The curves formed by each type of bold symbols are in fact limit curves for the highest \( D \) parameter. In [6], we showed that a family of curves is obtained when the sensor decay constant is selected and the number of superposed signals is two. Each curve of the family corresponds to a given Amplitude \( A_2 \) and an initial instant \( t_2 \) of the secondary signal.

In the present paper a new and more realistic estimation of sensor decay constant was calculated here, obtaining \( \beta = 0.01 \) \( \mu \)s\(^{-1} \), which was used in this paper, giving a sensor temporal resolution of about 100 \( \mu \)s.

TABLE 1: Linear correlation coefficients.

<table>
<thead>
<tr>
<th>TEST</th>
<th>A-D</th>
<th>A-R</th>
<th>D-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARI23</td>
<td>0.6976</td>
<td>0.3557</td>
<td>0.5713</td>
</tr>
<tr>
<td>ARI24</td>
<td>0.7589</td>
<td>0.2210</td>
<td>0.5165</td>
</tr>
<tr>
<td>ARI27</td>
<td>0.2527</td>
<td>-0.1455</td>
<td>0.7687</td>
</tr>
<tr>
<td>ARI28</td>
<td>0.8093</td>
<td>0.1735</td>
<td>0.4360</td>
</tr>
<tr>
<td>ARI29</td>
<td>0.8604</td>
<td>-0.0131</td>
<td>0.2762</td>
</tr>
<tr>
<td>ARI30</td>
<td>0.7070</td>
<td>0.1616</td>
<td>0.6285</td>
</tr>
<tr>
<td>ARI31</td>
<td>0.6826</td>
<td>0.2666</td>
<td>0.6826</td>
</tr>
<tr>
<td>ARI33</td>
<td>0.8604</td>
<td>-0.0680</td>
<td>0.0571</td>
</tr>
<tr>
<td>ARI34</td>
<td>0.4832</td>
<td>0.1445</td>
<td>0.4832</td>
</tr>
<tr>
<td>ARI35</td>
<td>0.8217</td>
<td>0.1857</td>
<td>0.3950</td>
</tr>
<tr>
<td>ARI36</td>
<td>0.9127</td>
<td>0.1785</td>
<td>0.3799</td>
</tr>
<tr>
<td>MAN2</td>
<td>0.5734</td>
<td>-0.2754</td>
<td>0.401</td>
</tr>
<tr>
<td>MAN3</td>
<td>0.6545</td>
<td>-0.1179</td>
<td>0.497</td>
</tr>
<tr>
<td>MAN4</td>
<td>0.4967</td>
<td>-0.2112</td>
<td>0.4518</td>
</tr>
<tr>
<td>MAN5</td>
<td>0.810</td>
<td>-0.2041</td>
<td>0.1706</td>
</tr>
<tr>
<td>MAN6</td>
<td>0.360</td>
<td>-0.837</td>
<td>0.423</td>
</tr>
<tr>
<td>MAN7</td>
<td>0.4775</td>
<td>0.1871</td>
<td>0.9361</td>
</tr>
</tbody>
</table>
FIGURE 1. Experimental points and theoretical curves, MAN2 test (with oxide layer).

FIGURE 2. Experimental points and theoretical curves, MAN6 test (without oxide layer).

FIGURE 3. Experimental points and theoretical curves, ARI29 test.
In the present work this result was generalised. For instance, when the superposition of three signals was considered and the sensor decay constant selected, a family of curves \( z \) vs. \( D \) was obtained, being each curve determined by \( A_2, t_2, A_3, t_3 \). For the limiting curves shown in Figures 1-3, these parameters were selected as to obtain the right border of the region. The numerical values were:

a) Bold rectangles: superposition of two events: \( A_2=7000 \text{ mV}, t_2=120 \mu\text{s} \)
b) Bold circles: superposition of three events: \( A_2=8000 \text{ mV}, t_2=120 \mu\text{s}, A_3=4500 \text{ mV}, t_3=250 \mu\text{s} \).
c) Bold triangles: superposition of five events: \( A_2=8000 \text{ mV}, t_2=120 \mu\text{s}, A_3=4500 \text{ mV}, t_3=250 \mu\text{s}, A_4=2000 \text{ mV}, t_4=370 \mu\text{s}, A_5=1000 \text{ mV}, t_5=490 \mu\text{s} \).

The case of superposition of four signals was not plotted for clarity.

When the initial times of secondary signals were considered, a previous analysis of the characteristic times of the involved physical processes had to be done. They were: typical times of possible AE sources in plastic deformation, time intervals involved in reflections according to the geometry of samples, sensor temporal resolution, sensor decay constant. N. Natsik and Chishko performed a theoretical estimation of the time employed by a Frank-Read source for the production of a dislocation loop, obtaining values between 0.06 \( \mu\text{s} \) and 50 \( \mu\text{s} \), depending on different conditions for the applied load and initial loop length. Imanaka, Sano and Shimizu estimated the time involved in the production of the same sources as 0.01 \( \mu\text{s} \). It is plausible to consider each grain in steel (diameter in the order of 30 \( \mu\text{m} \)) as the zone where replicas are produced, therefore, the minimum time for obtaining replicas would be of the order of 0.01 \( \mu\text{s} \), for a propagation speed of 3000 m/s [10].

Taking into account the geometry of MAN samples, it is necessary to consider the reflections of the bulk waves in each of the free surfaces configuring the thickness of the samples. According to their external dimensions, the involved times related with these primary reflections in these surfaces of the order of 6 \( \mu\text{s} \). [10].

If we consider surface waves and their reflections at the chord ends of the MAN test specimens, the distance involved is of the order of 37 cm, giving flight times of 125 \( \mu\text{s} \) coincident with our initial times for secondary signals. Thus, our model represents these reflections so as the subsequent reflections and transmissions of the surface waves. Moreover, considering that Amplitudes measured by our AEDOS system are up to 10000 mV, and taking into account that attenuation of elastic waves in metals in the involved distances is not important, the selected values of Amplitude for secondary waves were adequate.

Some MAN tests pieces had their oxide layer, in these cases, a higher level of AE was obtained. Considering that oxide layer breakdown is brittle, the velocity of crack advance is up to 3000 m/s, and assuming that the size of an oxide particle is 0.1 mm, times involved are about 0.03 \( \mu\text{s} \). Therefore, this fact can contribute with a lot of very near superposed signals, that cannot be resolved by the sensor, giving a very large unique signal. This fact would explain the experimental points in the highest Duration region, although some of them could also correspond to a unique signal of intrinsic large Duration. The small quantity of points to the left of the right line, fall inside experimental error.

CONCLUSIONS

In the present paper we continued studying the relation between \( A \) and \( D \) in the AE signals coming from deformation tests in steel samples and explosion tests in Zry tubes. We began analysing the correlation matrix for \( A, D \) and \( R \), finding an important correlation
between the former two parameters. The graph for the Logarithm of relative Amplitude versus Duration of AE signals was a cloud of points in a band between two slightly convex lines. If each burst is a simple event a unique straight line was expected. Following our previous paper, bursts were modelled as a superposition of a number of events: the original one and those obtained by successive reflections at adequate boundaries. To determine this boundaries the characteristic times of different involved physical processes had to be considered: typical times of possible AE sources in plastic deformation, time intervals involved in reflections according to the geometry of the samples and the sensor decay constant. In a graph of the Logarithm of relative Amplitude vs. Duration of the signals, with a selected sensor decay constant, our model conducted to families of convex lines with parameters related with the reflected events, one family for each number of superposition. When the considered number of superposition was higher the family of curves was displayed to the right region, where the $D$ parameter is higher. In many cases, each experimental point in the Logarithm of relative Amplitude vs. Duration graph, representing a complex event, could be interpreted as due to a determined number of reflections. In this way the fit between the experimental cloud of points and the calculated curves, conforming a map, was improved. In more complicated cases, including oxidised samples, a lot of very near superposed signals, that cannot be resolved by the sensor, could give a very large unique signal owed to the rupture of the oxide layer, located in the region of the map with higher $D$ values, corresponding by the way to a higher number of superposition. This fact would explain the experimental points in the highest $D$ region, although some of them could also correspond to a unique signal of intrinsic large Duration.

REFERENCES
