FROM NEAR FIELD TO FAR FIELD AND BEYOND

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Abstract

For proper localization and especially for accurate evaluation of acoustic emission source significance, it is necessary to obtain attenuation curve, which is defined as a dependence of the AE signal amplitude on the distance from the AE source. The attenuation curve is, according to EN14584 standard, further divided into two fields – near field and far field. The main aim of the following paper is to analyse effect of geometry on the attenuation curve. The authors have realized a series of measurements on geometries, which differ in size and wall thickness. It is shown that the geometry boundaries, in most cases, significantly influence the shape of attenuation curve in comparison to typical attenuation mechanisms like absorption, dissipation or dispersion. Just as significantly, the AE sensor type and the thickness of couplant layer influence the attenuation of the wave’s components with higher frequencies. Estimation of the scope of near field with respect to EN 14584 standard is discussed with the aid of gained experimental data.

Keywords: Near field, Far field, Attenuation curve, Refraction, Reflection, Dissipation, Dispersion, Absorption

1. Introduction

Acoustic emission (AE) is a phenomenon related to the radiation of elastic waves, generated by the release of energy, which is internally stored in a structure [1]. This well-known definition includes many types of waves with wide frequency range. However, the AE systems are designed to handle only a small part of the entire frequency spectrum. One of the basic problems associated with the applications of this method is detection and subsequent identification of elastic waves with use of sensors based on various principles (piezoelectric, capacitive, etc.). Elastic waves can be also detected in close proximity of cracks and in places with ongoing plastic deformation. From the characteristic properties of the AE signal we can, to a certain extent, specify type of the AE source and also its position. For these purposes, it is important to have the characteristics of the AE sensor and also the attenuation curve of the AE signal in a given part of the tested structure. The aim of this paper is, in according to practical experience, is to assess the factors affecting the overall character of the wave during its propagation from the AE source.

2. Wave propagation problems

As previously mentioned, acoustic emission method enables us to determine the moment when a defect or crack begins to propagate. Under certain conditions, it is also possible to determine the location of the source. The fundamental questions are the characteristics of the AE sensors and the change of AE signal during its propagation from the AE source to the AE sensor [1]. Especially, in case of pressure vessel testing, the proper measurement of attenuation curve is a crucial importance for subsequent qualitative assessment of tested
structure. In real structures, the propagation of elastic waves is influenced by two main factors:

1. Geometry of tested structure (shape complexity, amount of flanges, welds etc.)
2. Material properties (grain size, presence of inclusions, micro-cracks, heterogeneities, anisotropy of the material, non-linear elastic properties of material etc.)

2.1 Guided waves in plates

From mathematical point of view, there exist two types of waves: bulk waves and surface waves [2]. Bulk waves are propagating in the bulk of the material, while surface waves propagate only at the interface between two different media. Although bulk and surface waves [3,4] are fundamentally different, they can be described by the same set of partial differential wave equations [3]. The difference is, that for bulk waves, there are no boundary conditions, which need to be satisfied. Some of the most known guided waves, which have been mathematically described, are Rayleigh or Lamb waves.

Boundary conditions for Rayleigh wave:
\[ \sigma_z = \tau_{zx} = \tau_{zy} = 0 \text{ for } z = 0 \]

Boundary conditions for Lamb wave:
\[ \sigma_z = \tau_{zx} = 0 \text{ for } z = \pm d \]

For both types of waves can be the displacement vector defined as the sum of gradient of a potential function and the curl of a vector function [2]:

\[ \mathbf{u} = \text{div} \, \phi + \text{curl} \, \psi. \]  \hspace{1cm} (1)

Where the potential and vector functions are defined as follows:

\[ \phi = \phi(x, z) \text{ and } \psi = (0, -\psi(x, z), 0) \] \hspace{1cm} (2)

Using eq. (1) in the equation of motion, which is expressed in terms of displacements (see eq. (3)) will give us the governing equations for longitudinal and shear waves - eq. (4) and (5):

\[ \mu \nabla^2 \mathbf{u} + (\lambda + \mu) \nabla(\nabla \mathbf{u}) = \rho \ddot{\mathbf{u}} \] \hspace{1cm} (3)

\[ c_L^2 \nabla^2 \phi = \ddot{\phi} \] \hspace{1cm} (4)

\[ c_T^2 \nabla^2 \psi = \ddot{\psi} \] \hspace{1cm} (5)

where:

\[ c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{1}{\rho \sqrt{E(1 - \nu)}} \frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)}} \] \hspace{1cm} (6)

\[ c_T = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{1}{\rho \frac{E}{2(1 + \nu)}}} \] \hspace{1cm} (7)
\( \mu \) and \( \lambda \) are Lame’s constants, \( \nu \) is Poisson’s ration, \( \rho \) is the mass density per unit volume, \( \mathbf{u} \) is displacement vector, \( c_L \) is wave speed of dilatational waves, \( c_T \) wave speed of shear waves and \( (\cdot)^{\cdot} \) denotes the second derivative with respect to time. Considering harmonic wave motion for both types of waves and boundary conditions listed in Fig. 1, expressions for stress tensor and displacement vector components can be thereafter obtained.

Known phenomenon, which is related to the wave propagation is dispersion. In general case, dispersion refers to frequency dispersion, which means, that the velocity of wave is a function of frequency. The functional dependence between velocity and frequency is mainly caused by non-linear elastic behavior of the material. The wave packet is built up from a sum of waves of different frequencies, the dispersion will then cause the change of the wave shape and moreover, the wave will be now travelling with, so called, group velocity. The group velocity is the speed with which the energy carried by the wave travels through a medium.

Frequency dispersion is present in the vast majority of acoustic emission measurements. Especially in case of structures such as pressure vessels or storage pressure tanks of various dimensions plays frequency dispersion, among other phenomena related to the wave propagation, inconsiderable role. Lamb waves, together with Rayleigh waves, are common type of waves that occur in the above mentioned applications. Lamb waves are the product of conversion of dilatational, shear or even Rayleigh waves due to finite dimension of material layer \[5,6\].

The phase dispersion curves can be obtained by solving the Rayleigh-Lamb frequency equations:

\[
\text{real} \left[ \frac{\tan(qh)}{q} + \frac{4k^2 \tan(ph)}{(q^2 - k^2)^2} \right] = 0 \text{ for symmetric mode}
\] \hspace{1cm} (8)

\[
\text{real} \left[ q \tan(qh) + \frac{\tan(ph)(q^2 - k^2)^2}{4pk^2} \right] = 0 \text{ for asymmetric mode}
\] \hspace{1cm} (9)

where:

\[
p^2 = \left( \frac{\omega}{c_L} \right)^2 - k^2
\] \hspace{1cm} (10)

\[
q^2 = \left( \frac{\omega}{c_T} \right)^2 - k^2
\] \hspace{1cm} (11)

\( k \) is wavenumber, \( c_L \) is wave speed of dilatational waves, \( c_T \) wave speed of shear waves and \( \omega \) is angular frequency. The group velocity is defined as the slope of the tangent in particular point of \( \omega = f(k_{Re}) \) diagram \[2][3]:

\[
c_g = \frac{d\omega}{dk}
\] \hspace{1cm} (12)

Substituting \( k = \frac{\omega}{c_p} \) will result in formula \[3\]:

\[
c_g = d\omega \left[ d \left( \frac{\omega}{c_p} \right) \right]^{-1} = c_p^2 \left[ c_p - \omega \frac{dc_p}{d\omega} \right]^{-1}
\] \hspace{1cm} (13)

from where:

\[
c_g = c_p^2 \left[ c_p - (2f d) \frac{dc_p}{d(2f d)} \right]^{-1}
\] \hspace{1cm} (14)

where \( c_p \) is phase velocity, \( f \) denotes frequency and \( 2d \) is thickness of the material layer.
Following figures show us the dispersion curves in terms of dependencies: $c_p = f(fd)$ and $c_g = f(fd)$. The dispersion curves have been obtained using Python programming language with following input parameters: (Steel grade 11) $c_L = 5970$ m/s, $c_T = 3100$ m/s, $<0,15>$ frequency-thickness range [MHz mm].

![Fig. 2: Dispersion curves for $c_p = f(fd)$](image1)

![Fig. 3: Dispersion curves for $c_g = f(fd)$](image2)
3. Experimental Procedure and Results

Overall, there were used three different structures in order to study the behaviour of the elastic wave propagating from the AE source and as well as to assess the problematics of near and far field according to EN 14 584 [7]. They were the following structures:

1. Structure 1: Steel plate of dimensions 2500 x 1250 x 10 mm (Steel grade 11, surface roughness Ra 3,2)
2. Structure 2: Steel plate of dimensions 10000 x 2000 x 100 mm (Steel grade 11, surface roughness Ra 3,2)
3. Structure 3: Steel cylinder of dimensions 940 x 430 mm (diameter x height, surface roughness Ra 0,2-0,4)

As AE source, there were used either a pulse generator with attached SR 150 M acoustic emission sensor (resonance at 150 kHz, Soundwel Co. Ltd. manufacturer) or Hsu-Nielsen AE source (pencil lead of diameter 0,3 mm and 2H hardness). In case of pulse generator, the sensor has been excited by the rectangular pulse of amplitude, which varies from 3 to 10 Volts, and the pulse width was equal to 2 seconds. The generated AE signal has been measured by the same type of AE sensor, as used in a pulser regime. The amplification of the measured AE signal was carried out with presence of 40 dB preamplifier. The final signal processing has been done by oscilloscope connected to PC.

3.1 Results - structure 1

According to [7], the attenuation curve can be divided into two regions – near field and far field. Near field is characterized by rapid decrease of AE signal amplitude with distance due to geometry of tested structure as well as due to wave mode conversion. Distinctive feature of the far field is, unlike near field, a gradual decrease of AE signal amplitude with distance. Normative document [7] also mentions, that the approximate boundary between near field and far field is twenty times of the wall thickness. This assumption, however, applies for the case of simple structures [7]. Following figure shows the trend of decreasing signal amplitude as the function of distance from center of AE sensor. For structure 1, the authors have used Hsu-Nielsen AE source (pencil lead of diameter 0,3 mm and 2H hardness) instead of pulse generator. For each distance from the center of the sensor, there have realized three lead breaks, from which has been calculated an average value.

![Attenuation curve in case of structure 1](image)

It is obvious, that the attenuation curve in this case can be truly divided into two areas, where the near field’s border is situated at the distance between 100 and 150 mm. The attenuation
coefficient for near field is equal to 98 dB/m and for far field yields to the value of 14 dB/m. The next goal was to inspect the wave packet after travelled 300 mm from AE source (H-N source). For this purpose, there have been used two AE sensors of the same type, which were at the distances of 50 mm and 300 mm respectively from the AE source. According to the time of flight difference of particular mode and the known distance between AE sensors can be easily calculated the velocities for both modes (Fig. 5). The S0 mode has travelled with velocity equal to 4.54 mm/µs, while the A0 mode travelled with velocity 3.12 mm/µs. These velocities correspond to the frequency-thickness product, equal to 1.3÷1.5. According to the known thickness of the plate (10 mm) can be derived the wave frequency, which is equal to 130÷150 kHz. Such a value fully corresponds to the frequency emitted by the H-N source when applied to structures from steel.

![Fig. 5: S0 and A0 mode in structure 1](image)

3.2 Results - structure 2

The measurement of the attenuation curve in case of structure 2 was carried out for two artificial AE sources – N-H source (pencil lead of 0.3 mm dia. and 2H hardness, in each point three measurements of the amplitude from which has been calculated an average value) and pulse generator with SR 150 M acoustic emission sensor (rectangular pulse of 10V amplitude and pulse width of 2 seconds). Figures 6 and 7 depict normalized attenuation curves for which construction has been used Hsu-Nielsen source. Approximate end of near field seems to be at around 400/500 mm from the center of the AE sensor. The results in case of use of pulse generator are somewhat different. The border between near and far field seems to be between 600 and 850 mm from the center of the AE sensor. Thanks to relatively high frequency-thickness product and its associated larger amount of present symmetric and antisymmetric modes of Lamb wave, the authors haven’t made any further analyses of particular modes of Lamb wave. However, the average velocity of the wave packet has stabilized at a value of 3.15 mm/µs which corresponds to the group velocity of both modes of Lamb wave for higher values of frequency-thickness product.
3.3 Results - structure 3

In case of structure 3, which was represented by steel cylinder of dimensions 940 x 430 mm, the measurement of the attenuation curve was carried out by use of N-H source (pencil lead of 0,3 mm dia. and 2H hardness, in each point three measurements of the amplitude from which has been calculated an average value). The maximum distance, in which has been measured the amplitude of the generated elastic wave, was 650 mm from the center of the AE sensor.
The transition between earlier defined near and far field lies between 100 and 120 mm from the center of the AE sensor. Thanks to relatively high height of the cylinder, the propagating elastic wave, in this case the Rayleigh wave, hasn’t been significantly impeded by the reflections from free surfaces. The trends of the attenuation curve have almost linear character in both segments.

Fig. 8: Attenuation curve in case of structure 3

4. Conclusion and discussion

Knowledge of the mechanisms of propagation of guided waves in case of pressure vessels is an essential knowledge for further positional scheme of AE sensors as well as for proper evaluation of AE sources. Results, obtained on steel plates of thicknesses 10 and 100 mm and also on steel cylinder confirm high influence of geometry on the attenuation of elastic waves and the shape of the wave packet. The validity of the near field length according to [7] hasn’t been confirmed. On the contrary, the results from realized measurements demonstrate, that the border of the near field lies between 100 and 850 mm from the center of the AE sensor depending on the type of the AE source and the thickness of the material layer through which the wave is propagating. With help of supplementary measurements, there was observed very strong dependence between the quality of sensor attachment on the surface of tested structure and the attenuation coefficients for both near and far field. When the installation of the AE sensor is made poorly, it is impossible to find significant boundary between near and far field. This finding is, however, connected with a rapid attenuation of the pulses with higher frequencies thanks to poorly made acoustic coupling. From this implies, that the quality of sensor attachment could be in certain cases assessed by the attenuation coefficients for near and far field. Furthermore, the realized measurements pointed to the limitations of used AE sensors in terms of their frequency range and the principle on which they work. Ideal broadband piezoelectric AE sensor with required sensitivity practically doesn’t exist. Therefore, it is necessary to find the frequency range at which is the violation of the structural integrity on particular structure most significant and subsequently use a resonant sensor with dedicated frequency range. In other words, it would be necessary to create a dedicated testing procedures for each tested structure including detailed analyses of AE sources which could occur on tested structures.
References

7. EN 14584 Non-destructive testing – Acoustic emission testing – Examination of metallic pressure equipment during proof testing – Planar location of AE sources