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Numerical modeling of existing acoustic emission sensor absolute calibration approaches

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ABSTRACT

Within recent years, several alternative approaches to acoustic emission sensor calibration have been proposed. As some of these approaches make use of new geometries and materials, the aspect of absolute calibration in the context of these proposals is evaluated in this contribution. Validated numerical methods are applied to compare the expected acoustic emission sensor sensitivity in a variety of material and geometry configurations. The numerical approach uses a coupled structural and piezoelectric formulation in combination with electric circuit modeling. Established routines allow obtaining the sensitivity versus frequency curve as sensor response in electrical voltage per meters displacement. This study is performed for one previously used conical sensor design and one typical disc type sensor design to examine the impact of the investigated approaches for these different sensor dimensions and designs. Specific attention is paid to the influence of the propagation medium material properties, the chosen wave type and the geometry of the propagation medium. For use of plate-like propagation media further aspects, such as thickness, distance and formation of guided wave modes are evaluated. A primary result is that there is a significant influence to be expected for calibration attempts with different wave types for the same material, which can be of particular relevance when using sensor systems with extended aperture, such as common to most of the commercial sensors.

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1. Introduction

Early complete methods for the absolute calibration of acoustic emission (AE) sensors came quite a few years after the first commercial AE sensors were available in the late 1960s. The first publication in 1976 described a reciprocity-based method developed in Japan [1]. The approach used electrical signals to generate waves. The second publication in 1982 described an alternate method developed in the United States based on waves generated by the fracture of a glass capillary [2]. Both of these methods relied on the use of very large steel blocks as the wave transmission medium. The large blocks were used to eliminate reflections from the boundaries. In the case of both methods, the waves present were limited to bulk waves and Rayleigh waves. The first method was adopted as a standard NDIS 2109 in 1991, and the second method was adopted as a standard ASTM E1106 in 1986. Later approaches in the United Kingdom started to evaluate the use of laser vibrometers for signal referencing [3] instead of the capacitive sensor used before [4]. Recently two new geometries have been proposed. These both use guided waves. In one case, plate geometry is used [5] as the wave propagation media and in the other case, rod geometry is used [6] as the wave propagation media. Apart from these approaches, the direct coupling of the sensor under test and an actuator, commonly referred to as face-to-face method, is frequently used. The shortcomings of this method are extensively discussed in [7], so these are not repeated here. The above brief history of sensor calibration (with associated experiments) is not intended as a comprehensive review that would include the many follow-on works.

This work is directed not towards calibration with associated experiments but at modeling wave-propagation in media along with modeling the associated sensor calibrations. This modeling approach has several benefits, but also some drawbacks. On the beneficial side, the modeling approach provides very good control over experimentally inaccessible parameters and allows evaluation of all involved physical quantities at arbitrary locations. Also, the visualization of the wave propagation by itself is helpful to understand and discuss boundary and geometry effects on the recorded AE signals. In addition, an initial modeling of calibration may avoid costs to carry out extensive experimental campaigns. However, the

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Table 1
Structural material properties used in this study.

Name	Density [kg/m^3]	Modulus [GPa]	Poisson's ratio
Steel	7800	210.9	0.33
Polymethylmethacrylate (PMMA)	1160	6.2	0.32
Aluminum	2660	70.0	0.33
Steel casing	7850	200.0	0.33
Ag-Epoxy adhesive	1700	2.7	0.45
Brass backing	8530	113.4	0.33
Wear plate	3965	400.0	0.22
Lead-Zirconate-Titanate (PZT)-5A	7750	$C_{11} = C_{22} = 120.3$ $C_{12} = 75.2$ $C_{13} = C_{23} = 75.1$ $C_{33} = 110.9$ $C_{44} = C_{55} = 21.1$ $C_{66} = 22.6$	–

main potential drawback certainly is the reliability of the modeling procedure. Throughout several previous publications we have established a numerical routine, which is capable of predicting the AE sensor response in sensor calibration situations [8–10]. The overall feasibility of such approaches has also been shown by other groups (e.g. in [11,12]) for direct epicenter wave front arrivals after short distance of propagation (<12.7 mm) with a signal duration allowing multiple reflections from the bottom to top of the plate propagation medium. In this study, the modeling approach uses a propagation distance of 100 mm for the propagation media. With reference to established standards, the size of the propagation media is chosen to allow detection free of reflections. Then four cases are considered for two very different sensors. Subsequently, the principle findings of this study are presented and several factors of influence, such as wave propagation mode(s), choice of material, sensor design, and implications of using Lamb waves are elucidated. Particular emphasis is given to elaborate the use of Lamb waves for potential use for AE absolute sensor calibration procedures. If such a propagation medium could be used, it would make it much easier to obtain and use such a medium. No focus is given to the face-to-face approach, as we do not consider this an absolute calibration method.

2. Modeling approach

All numerical computations are carried out within the software program Comsol Multiphysics 5.2a using the "Structural Mechanics Module" and the "AC/DC Module". The software program uses an implicit formulation in order to solve transient coupled partial differential equations. The principle settings follow the validated approach established in [9] and apply the full 3D coupled piezoelectric equations in combination with a P-SPICE circuit simulation to account for the attached electronics such as preamplifiers and acquisition electronics.

2.1. Model configuration

Within the numerical framework, four principle case studies for AE sensor calibration are investigated. These are summarized in Fig. 1, which includes their dimensions. All material properties used are listed in Table 1.

2.1.1. Model geometries

The first case considers the typical arrangement with a test source opposite to the test sensor, separated by a large cylinder-type propagation medium. As test source function, an emulation of the rise time of a glass capillary fracture is used. This is done by a force function applied at a circular contact area with radius $r_s = 0.5$ mm. The force is applied in the z-direction using a cosine-bell shape function reaching a maximum $F_m = 10\,N$ within a rise-time $t_s = 0.3\,\mu$s [13,14] following the values in the current version of ASTM E1106-12:

$$F(t) = \begin{cases} \frac{F_m}{2} \cdot \left(1 - \cos\left(\frac{\pi t}{t_s}\right)\right) & t \le t_s \\ 1 & t > t_s \end{cases} \qquad (1)$$

The AE sensor under investigation is located at 100 mm opposite (epicenter) to the source position with the AE sensor geometries found in Fig. 2. In this configuration, the wave propagation mode is solely longitudinal and transversal waves arriving at the sensor position. The radius of the cylinder is large enough to avoid interference of reflected waves at the AE sensor position within the first 50 μs for a steel block. As the geometry of the first case is fully axisymmetric, the computation was carried out with a central axis of symmetry.

For the second case, the radius of the propagation medium is reduced to yield a typical rod configuration. While all other settings are kept identical to the first case, the change in boundary constraints now forces a guided wave propagation mode in the form of rod waves. Again, the computation was carried out in an axisymmetric geometry. Due to the symmetry axis at x = 0 mm, the only allowed guided wave modes for frequencies up to 1 MHz are the L(0,1), L(0,2), L(0,3) and L(0,4) rod wave modes for the source position at x = 0 mm. The 100 mm length of the rod was such that no end reflections were present in the first 55 μs for a steel rod.

As a third case, the arrangement of test source and AE sensor is changed relative to the first case. As seen in Fig. 1-c, the test source function is now applied at the top of the cylinder with the center of the AE sensor offset by 100 mm. In this configuration, the test source function of Eq. (1) is applied in the minus z-direction. Besides the longitudinal and transversal waves, this source also initiates a Rayleigh wave spreading on the top surface of the cylinder. In this configuration, the Rayleigh wave is the dominant wave mode detected by the AE sensor. Due to the break of symmetry, it is no longer feasible to model the configuration by an axisymmetric approach. Instead, the "general extrusion coupling feature" of Comsol Multiphyiscs was applied to link a 2D wave propagation model with a 3D half-volume AE sensor representation (see below for details of 2D-3D coupling). The dimensions of the cylinder were such that no significant reflections were present in the first 68 μs for a steel cylinder.

The fourth case is a direct extension of the third case. Keeping all settings identical, the thickness of the cylinder was reduced to yield a thin plate of 3 mm thickness. Accordingly, the wave propagation from the test source to the sensor changes, and the wave travels as distinct Lamb wave modes due to the large ratio of the propagation distance of 100 mm to the plate thickness. For the frequency range up to 1 MHz, these modes are the antisymmetric (A_0 and A_1) and symmetric (S_0 and S_1) Lamb wave modes. For a steel plate, the outer radius was such that no edge reflections were present during the first 70 μs.

2.1.2. Sensor implementation

For this study, two representative AE sensor models were chosen. As first choice, a cone shaped PZT-5A element with brass backing mass, representative of typical conical sensors was selected. The dimensions and implementation of this AE sensor model is consistent with the settings reported in [9]. As second choice, a cylindrical, disc-type PZT-5A element with epoxy adhesive bonding, ceramic wear plate and metallic sensor casing was used. The dimensions of these elements conform to typical values found in commercial resonant type AE sensors. In both cases, the

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