Simulation of the spatial frequency-dependent sensitivities of Acoustic Emission sensors

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Abstract. Typical configurations of nondestructive testing by Acoustic Emission (NDT/AE) make use of multiple sensors positioned on the tested structure for detecting evolving flaws and possibly locating them by triangulation. Sensors positions must be optimized for ensuring global coverage sensitivity to AE events and minimizing their number. A simulator of NDT/AE is under development to provide help with designing testing configurations and with interpreting measurements. A global model performs sub-models simulating the various phenomena taking place at different spatial and temporal scales (crack growth, AE source and radiation, wave propagation in the structure, reception by sensors). In this context, accurate modelling of sensors behaviour must be developed. These sensors generally consist of a cylindrical piezoelectric element of radius approximately equal to its thickness, without damping and bonded to its case. Sensors themselves are bonded to the structure being tested. Here, a multiphysics finite element simulation tool is used to study the complex behaviour of AE sensor. The simulated behaviour is shown to accurately reproduce the high-amplitude measured contributions used in the AE practice.

1. Introduction

Acoustic Emission (AE) is a widely used nondestructive testing (NDT) technique, known to be very sensitive to early damaging processes in possibly very large industrial structures. It is a passive technique where the source of elastic waves is typically an evolving defect and where AE sensors are positioned (possibly permanently attached) onto the structure. The number and the positions of sensors must be optimized so that any event can be detected wherever it happens in the component under test (full coverage must be ensured) with a minimal number of sensors for obvious economic reasons (number of independent channels to manage etc.). The method is known to offer high detection capabilities. It can further be used for defect location. For this, several sensors must detect the same AE event, and measure the arrival time at each of these sensor positions. Then, assuming the wave speed in the structure is known, triangulation algorithms can be applied to locate the source of the AE event.

However, typically measured AE time-dependent signals are complex. Physical phenomena taking place are of various nature and involve various space and time scales, from [\mu m] and less than [\mu s] for crack propagation to [m] and more than [ms] for wave propagation. Accounting for a single wave speed in the structure – a necessary assumption for applying simple triangulation – often constitutes an over-simplification of actual elastic wave propagation in an industrial structure, all the more since waves propagating as guided waves are involved (in thin structures). For these reasons, AE testing is not considered as being a quantitative nondestructive technique. Despite the non-quantitative nature of
the technique, the availability of a simulation tool that can address this complexity would constitute a useful mean for optimizing AE testing configurations and for helping the interpretation of measured signals. The development of such tools attracts far less people than that of tools for simulating more quantitative techniques (ultrasonic, eddy-current, radiography). Several objectives of such developments can be identified. A first objective is to get accurate knowledge about influencing parameters among the many parameters involved [1]; simplifications can be considered so that some parameters can be treated independently of the others. Once this objective is reached, tools able to deal with realistic configurations must be developed to attain the second and more ambitious objective of predicting typical signals at several sensor locations, given one AE event, one component under test and assuming sensor sensitivity is known. This implies to model AE events (for example crack evolution in metallic parts [2], damage in composites [3]), elastic wave propagation in a component [4] and the behaviour of AE sensors [5]. References 1, 2, 4 and 5 correspond to a first attempt at CEA to pave the path for the development of a simulation tool of AE testing to be included in the CIVA platform [6].

The present paper addresses the problem of predicting sensor sensitivity. Evidences of a complex behaviour of standard AE sensors led to the development of various methods to characterize them experimentally over the last decades. A recent review can be found [7] where results obtained by the main methods and applied to the same sensors are compared. Clearly, each method accesses to some characteristics of the sensor behaviour, but not all to the same ones. In other words, the characterization obtained by these various methods is incomplete. In the present study, our goal is to predict this behaviour (as done in the case of conical AE sensor [8]) to understand what makes it complex, to check experimentally the validity of predicted results to further deduce from this knowledge a strategy to include sensor simulation in a global AE testing tool.

2. Sensitivity of acoustic emission sensor

To predict the sensitivity behaviour of an AE sensor, we first briefly discuss the notion of sensitivity and assumptions or even simplifications made in the AE community about it.

A typical AE sensor can be regarded as a linear system with a mechanical input (particle velocity, particle displacement, force…), and with a voltage as output. Its sensitivity function is used to describe its voltage response to an arbitrary incoming wave. Sensor sensitivity is said to be measurable by means of calibration methods such as step-force calibration, calibration by laser interferometer, face-to-face calibration or reciprocity calibration [7].

Sensors are supposed to respond to a weighted average of the mechanical input, relating to diffraction effects due to its finite aperture [9]. The sensitivity is described as a spatially dependent function over the sensor front face S in contact with the part. A classical form to account for aperture effects writes

\[ V(t) = \frac{1}{S} \int_S A(r) \cdot u(r, t) dS , \]  

where \( r \) denotes a running position at \( S \), \( t \) the time, \( V(t) \) the open circuit voltage, \( A(r) \) the local sensitivity vector and \( u(r, t) \) the particle displacement associated to the incoming wave at the surface. Further, in most cases, only the normal component of the displacement is considered. This writing means that \( A(r) \) is not considered to be time (or frequency) dependent. A common approximation considers that the sensitivity is scalar and uniform [10], \( A(r) \sim A_0 \). Under these approximations, Eq. (1) reduces to

\[ V(t) \approx \frac{A_0}{S} \int_S u_z(r, t) dS . \]  

This rather rough simplification for local sensitivity function is generally justified by the fact that, since most AE sensors are axisymmetric, tangential components of a normally incident wave vanishes by averaging effect so that only its normal component makes an effective contribution. Deviations
between experimental and computed aperture function in [10] probably comes from the strong assumption of uniform local sensitivity. A less restrictive assumption has been used in [5] by considering the local sensitivity as a function of the position at the sensor surface leading to improve the theoretical expression of aperture function. In that case, local sensitivity can be written as

\[ A(r) = A_0 \psi(r) e^{-i\phi(r)}, \]  

(3)

where \( A_0 \) is the maximum sensitivity to normal displacement of the sensor surface, \( \phi(r) \) the phase shift of this displacement and \( \psi(r) \), a weighting function. The output voltage becomes:

\[ V(t) \approx A_0 \int_S \psi(r) e^{-i\phi(r)} u_z(r, t) dS. \]  

(4)

In the next section, we will show that previous approximations are not valid. As so, calibration methods designed to characterize over-approximated sensitivities lead to experimental uncertainties.

3. Finite element modelling of AE sensor

3.1. Finite element configuration

To understand the actual behaviour of AE sensors, COMSOL Multiphysics finite element (FE) software has been used to carry out FE simulations [11]. The sensor being studied is a typical resonant one, developed by CETIM, and shown in Fig. 1. A thick piezoelectric element (PZT) is glued inside the sensor case onto which a cap is screwed. In the configuration of computation, the sensor is coupled to a hemispherical elastic medium surrounded by a perfectly matched layer (PML) to block wave reflections; this models a semi-infinite elastic solid. Classical PML for elastodynamics as implemented in COMSOL are used for computations in the frequency domain. Their validity has been very simply checked by means of numerical experiments showing that an outgoing wavefield does not give rise to reflected contributions from the interface between the modelled elastic medium and the PML.

![Figure 1. Configuration considered for FE computation of AE sensor behaviour](image)

AE sensors without preamplifier are reversible and can be used as a transmitter. Calibration methods based on reciprocity make use of this possibility. It is also useful for studying the sensor behaviour by the FE method. Generally speaking, FE studies where elastic wave phenomena are involved are costly in computation time and in memory because of the need for finely meshing the whole configuration, notably to account for wave propagation in thin layers. Considering a part of large volume comprising an AE source distant from the sensor to be modelled with a full account of 3D effects would be difficult to deal with. Conversely, modelling the sensor behaving as an emitter
allows us to reduce to a minimum the meshed elastic medium to which it is attached. Indeed, the active source is the sensor itself so that a small volume for modelling the part is enough to take into account its mechanical influence on sensor behaviour, once non-reflecting boundary conditions are chosen to close the volume at a short distance. Furthermore, considering the behaviour of the sensor acting as an emitter allows us to account for its axisymmetry, thus, to considerably reduce the size of the FE system to solve and the associated computation time, by modelling the whole configuration by means of axially symmetric elements.

In such a configuration, the various modes (thickness-modes, radial modes and more complex modes involving radial and thickness coupling) of the thick piezo-element are excited. In what follows, to finely capture the complex behaviour of the sensor, simulations are mostly carried out in the frequency domain over the typical bandwidth of AE sensor (1-1000 kHz), though computations in the time-domain are also made when full-waveforms are predicted and compared to experimentally measured signals.

3.2. Uniform sensitivity and contactless sensitivity measurement

In [5], non-uniformity of the sensitivity over the sensor front face has been demonstrated experimentally. In these measurements, an AE sensor is used as a transmitter radiating in air (unloaded); contactless point measurements of time-dependent velocity over the sensor surface are made by laser velocimetry. Then, a Fourier transform is performed to analyse it over the bandwidth of interest.

The FE model allows us to simulate such an experiment directly in the frequency domain. Simulation is also used to compute the velocity at the same points when the sensor is bonded to a solid (loaded case). Figure 2 compares the modulus of the particle velocity at 419 kHz for the unloaded case and for the loaded one. Obviously, the local velocity is far from being uniform as already mentioned in [5]. Now, it also clearly appears that the unloaded and the loaded cases lead to two different profiles.

![Figure 2. Local velocity modulus at the sensor surface for an excitation frequency of 419 kHz. a) the sensor is free, b) the sensor is in contact with semi-infinite medium made of steel](image)

Another way to illustrate the difference between these two cases is shown by Fig. 3 which represents the normal particle velocity averaged over the sensor face as a function of the excitation frequency.
The loaded case leads to a response which is smoother and of lower amplitude than the free case. In the loaded case, transmission from the sensor to the elastic medium is high (small impedance mismatch). In the free case, waves in the sensor are trapped since they cannot be radiated due to the huge impedance mismatch, this leading to both higher amplitude of waves and further resonances.

3.3. **Influence of radial displacement**

Considering results obtained for the loaded case can improve accuracy in determining the actual aperture function of the sensitivity as defined in [5], though a method for its measurement is to be invented for accessing to local mechanical quantities in the presence of a solid part. However, one of the main assumptions made in the literature and in the formulation involving an aperture function is that the sensor is sensitive only to normal component.

Now, AE sensors comprise cylindrical piezo-elements of radius approximately equal to their thickness, glued to the sensor case. Resonances of such elements are not restricted to a harmonic series of thickness resonances but inevitably include others involving radial modes or coupling radial and thickness vibration modes. Sensors are therefore sensitive to both normal and tangential contributions associated to incoming waves. In order to compare the influence these modes of the piezo-element on sensor behaviour, one can compute the ratio between the averaged radial and the averaged normal displacements along a radius of the sensor surface over the whole bandwidth, generated by the sensor used as an emitter. If the average was computed over the surface rather that along the radius, the averaged tangential displacement would be equal to zero as the sensor is axisymmetrical.

Two cases are shown in Fig. 4. In the first case, the sensor is mounted on a semi-infinite medium, whereas in the second one, it is mounted on an infinite 3-mm-thick plate. In both cases, the frequency-dependent above-defined ratio is shown together with a “smoothed” version of it to ease its reading. The smoothing is obtained by applying a classical Savitzky-Golay filter, as done in [7].
At first, one can observe that the averaged radial displacement is of the same order of magnitude as the normal one. Interestingly, depending on the geometry of the medium in which the transducer radiates, frequency-dependent ratios differ. In the plate, the radial displacement is even higher than the normal displacement in the range 400 to 600 kHz. Thus, it can be more accurate to consider not only the normal displacement in calibration techniques but also the radial one.

Finally, the most complete sensor response that can be simulated accounts for both normal and tangential sensitivities, for their nonuniform value along the radius of the sensor front face, and for their variation with the frequency. These sensitivities are obtained by computing in the frequency domain the surface traction \( T_E(\mathbf{r}, f) \) at the interface between the AE sensor and the part (modelled as a semi-infinite medium), by considering that the sensor is used as an emitter, excited by an alternative current \( I_E \) (same amplitude over the bandwidth \([0; 1]\) MHz).

We have shown [12], using the electromechanical reciprocity principle [13], that the output voltage produced by an incoming wave of particle velocity \( \mathbf{v}_R(\mathbf{r}, f) \) incident on the sensor surface, can be written as

\[
V(f) = \frac{1}{I_E} \int_S T_E(\mathbf{r}, f) \cdot \mathbf{v}_R(\mathbf{r}, f) dS.
\]  

According to Eq. (1), the sensitivity function \( A(\mathbf{r}, f) \) written in the frequency domain is given by

\[
A(\mathbf{r}, f) = \frac{i2\pi f \mathcal{S}}{I_E} T_E(\mathbf{r}, f).
\]  

It is not the purpose to give the full demonstration of this theoretical result which is out of the scope of the present paper. The two sensitivity functions (normal and tangential) are shown on Fig. 5 as two colour maps of their amplitude (in dB) as functions of the frequency and of the distance of the running position at the sensor front face from the centre of symmetry. The tangential sensitivity is displayed relatively to the maximum of the normal sensitivity to ease the reading of their relative values.

These results demonstrate once more that the sensitivity functions are not spatially uniform, are frequency-dependent and that the sensitivity to tangential displacement cannot be neglected.

4. Experimental validation

In order to perform some experimental validations of our FE computations, we set-up the experiment schematized by Fig. 6. An AE sensor used as a transmitter is mounted on a 3-mm-thick aluminium plate. Normal displacement at the surface of the plate is measured by a laser interferometer which
scans the plate surface at a set of points of a Cartesian 2D grid. At each position, the absolute time-dependent waveform measured by the interferometer is recorded.

Radiation into a plate is a more complex case than that into a massive elastic solid as, over the frequency bandwidth considered, elastic waves radiated in the plate propagate as guided waves which are multimodal and dispersive. This configuration is however of interest as many practical cases relevant to AE testing concern “thin” structures which involve propagation of elastic guided waves.

A snapshot of the measured normal displacement is displayed in Fig. 6. The emitter is at the centre of the map. The presence of the coaxial cable used for electrical excitation to the sensor manifests as a dark vertical line between the sensor and the bottom of the map. Figure 6 also displays the electrical excitation used in both the experiments and for the simulated results which follow.

Let us now compare simulated and measured waveforms. Since the area of interest is around the sensor position, Low-Reflecting Boundaries (LRB), specific to time-dependent computations in COMSOL [11], are introduced to absorb outgoing waves so that no edge-reflected contribution can superimpose with waves directly radiated by the source. In the experiment, the plate is large but of course finite so that waves reflected at the plate edges eventually superimpose with the directly radiated field. Therefore, the signal recorded in the experiments is time-windowed so that only the direct contributions are recorded.

Figure 7 compares simulated and measured waveforms for the normal particle displacement of the top surface of the plate at a point 50 mm distant from the source centre. The two waveforms are displayed in absolute amplitude, the same amplitude of electrical excitation being considered for both results.
The first wave packets are very well predicted by the simulation, both qualitatively for the shape of the waveform and quantitatively for its absolute amplitude. This clearly demonstrates the overall relevance of the ways the sensor, its excitation and the wave radiation are modelled. The accuracy of prediction for the wave packets arriving at longer time-of-flight is however far lower.

It is quite difficult to identify the very reasons for this lack of accuracy in the later packets. There are uncertainties in the values of some parameters. A sensitivity analysis was carried out where the values of selected model input parameters were varied. For example, the influence of glue thickness inside the sensor case or that of the elastic characteristics of the thin coupling medium between the sensor and the part have been studied. None of them had a quantitatively significant impact and the details of this sensitivity analysis are beyond the scope of this paper.

The actual sensor geometry is not exactly axisymmetric (flat surfaces are machined to hold the sensor more easily), as shown in Fig. 8, whereas in the computations, as mentioned above, the choice of purely axisymmetric configuration was made as it leads to solve far smaller FE systems. However, the influence of this simplification has been studied: it is very small and cannot explain the lower accuracy of predicted secondary wave packets.
simulation results. To show this, it is interesting to first make an extreme simplification to model the sensor case consisting in not considering it at all. The simulated waveform for the case of a piezo-element directly coupled to the plate is compared to the measured waveform, as displayed in Fig. 9. Interestingly, the order of magnitude is still the same, and the very first oscillations are quite similar. But the predicted waveform shows large resonances that are not present in the measured signal, thus demonstrating that the sensor case has an obvious role in the process.

Figure 9. Simulated (red) and measured (blue) waveforms of normal particle velocity at a point distant of 50 mm from the centre of the AE sensor. In the simulation, the piezo element is directly coupled to the plate.

To show this very clearly, a map of the particle displacement is given on Fig. 10, for a CW excitation at the frequency of 150 kHz. Again, since we are now in the frequency domain, PML boundary conditions are used at the top of the sensor connector and cable as well as in the plate. The particle displacement has significant amplitude in the PZT element but also in the sensor case.

Figure 10. Map of the particle displacement (module, absolute amplitude) for a CW excitation @ 150 kHz.
Now, if the cap modelled for the result given by Fig. 7 is replaced by artificial boundary conditions (LRB in the time domain), the predicted waveform shown in Fig. 11 differs from that accounting for the cap (but not accounting for the coaxial cable). Some energy is lost in the LRB layer which otherwise would propagate through the cap to eventually contribute to the radiated field.

Figure 11. Simulated (red) and measured (blue) waveforms of normal particle velocity at a point distant of 50 mm from the centre of the AE sensor. In the simulation, the sensor cap is replaced by PML boundary conditions.

This time, there are discrepancies at the end of the first packet (between 50 and 75 µs) but the amplitude of secondary packets (after 100 µs) agrees better with that of the measured waveform.

These simulation results establish that the field radiated by the sensor, and by reciprocity, the sensitivity of the sensor, strongly depends on the geometry of the sensor case. The geometry must therefore be accounted for, if an accurate prediction of its behaviour is sought. In the present case, treated as an example to study the complex behaviour of AE sensors, the actual behaviour would probably be better predicted by accounting for the complex structure of the cap, by including the presence of the coaxial cable and the way it is screwed to the case, the cap itself being screwed to the sensor case.

5. Discussions and conclusions
The simulation study by means of FE computations highlighted several salient characteristics of the behaviour of typical AE sensors.

First, their simple design leads to complex behaviour. The broadband sensitivity of AE sensors is obtained through the use of a thick cylindrical piezo-element, a geometry leading to a large number of eigen-modes in the frequency band of interest. Resonances are not smoothed by backing the element, a standard way for broadening the bandwidth of an ultrasonic transducer with a thin piezo-element typical of those used in ultrasonic testing; the smoothing of resonances results from complex propagation into the sensor case in which the element is glued. As waves propagate into the sensor case, the case design itself affects the overall sensitivity through a complex coupling of the piezo-element with the other elements constituting the sensor.

As a result of the above factors, the sensitivity is not simple to describe. Idealized AE sensor behaviour modelled as a uniform sensitivity to normal displacement, possibly refined by taking into account a variation with frequency, is too strong an approximation of the actual behaviour of AE sensor. Rather, it is nonuniform over the sensor front face in contact with the part under examination; furthermore, the nonuniform function of position is frequency-dependent. Furthermore, it depends on the mechanical loading exerted by the part on which the sensor is attached.
Finally, in order for it to be thoroughly described, the sensitivity function must be defined as a vector function comprising tangential and normal components which are complex-valued, which depend on two variables, namely, the frequency and the position over the surface in mechanical contact with the part. As the mechanical loading modifies the sensitivity, a better image would be that of a family of functions, parametrized by mechanical characteristics of the piece under test.

Standard experimental methods of AE sensor characterization only partially capture the complex behaviour of these sensors. Knowledge gained in accurately predicting this behaviour will help devise new methods for a full characterization of AE sensors.

References
[1] Lhémery A, Ben Tahar M, Foucher F, Mesinele A, Recolin P, Zhang F 2011 COFREND Conference Proceedings http://www.ndt.net/article/cofrend2011/papers/237.pdf,
[2] Hello G, Ben Tahar M, Roelandt J-M 2012 Int. J. Solids Struct. 49 556
[3] Sause M G R 2016 In Situ Monitoring of Fiber-Reinforced Composites - Theory, Basic Concepts, Methods, and Applications (Springer Int. Publishing, Switzerland)
[4] Ben Khalifa W, Jezzine K, Grondel S, Hello G, Lhémery A 2012 J. Acoust. Emission 30 137
[5] Monnier T, Dia S, Godin N, Zhang F 2012 J. Acoust. Emission 30 152
[6] Details about capabilities and uses of CIVA platform: http://www.extende.com/
[7] Ono K Materials 2016, 9, 508 (corrections: Ono K Materials 2016, 9, 784)
[8] Sause M G R, Hamstad M A, Horn S 2012 Sensors and Actuators A: Physical 184 64
[9] ASTM 1987 Non Destructive Testing Handbook: Acoustic Emission Testing 2nd edition (Columbus, OH: American Society for Non Destructive Testing) pp 126-130
[10] Goujon L and Baboux J-C 2003 Meas. Sci. Technol. 14 903
[11] COMSOL Multiphysics ® 2015. Version 5.2. COMSOL, Inc., Burlington, MA, USA. Users’ guide
[12] Boulay N, Lhémery A 2017 in preparation for NDT&E Int.
[13] Auld B A 1979 Wave Motion 1 3