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# Acoustic Emission modeling from the source to the detected signal: model validation and identification of relevant descriptors

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**ABSTRACT:** The interpretation of data measured by Acoustic Emission (AE) is largely based on empirical correlations between the respective characteristics of the source and the measured signal. The main limitation is that changes due to the acquisition chain are not well known. Therefore, the aim of this work is to build a quantitative relationship between the AE sources and the detected signal by unravelling the effect of the different stages of the acquisition chain. For this purpose, an AE modelling, in which each part is considered individually, is carried out. This will serve to understand the effects of different parameters on the signal waveform, such as the type of damage, the geometry of the specimen and the effect of the piezoelectric sensor.

## 1 INTRODUCTION

Acoustic Emission (AE) is a method for non-destructive evaluation allowing real time detection of damage mechanisms. As a consequence, it appears as a well-suited technique to retrace damage evolution in metals and composite materials. In fact, microscopic events occurring in the material during damage are at the origin of ultrasonic waves, which propagate up to the surface. Using AE sensors, it is possible to measure the surface vibrations due to the propagated waves. The analysis of the recorded signal gives some information about the source mechanisms, which are responsible for the wave generation. The common practice consists in describing the measured signal through some appropriate parameters (rise time, peak amplitude, centroid frequency, peak frequency, etc.), and regrouping signals into clusters thanks to classification algorithms [1]. The objective is to identify separate clusters corresponding each corresponding to a different source mechanism. However, the wave originating from the source is altered during propagation. Hence, the main limitation of the AE techniques is that changes due to the acquisition chain are not well known. First, it is modified by the propagation medium itself (phase displacement, reflections, dispersion) [2] and then, by the recording system. All these transformations make the interpretation of the signals very difficult. In other words, we would like to discern the role of the source from the effect of the transformations due to the propagation medium and the recording system on the measured signal. An experimental study alone cannot provide a satisfying answer.

Therefore, the aim of this work is to build a quantitative relationship between the AE sources and the detected signal by unravelling the effect of each stage of the acquisition chain, namely the source, the propagation medium and the detection system. For this purpose, an AE modelling is carried out using the finite element method (FEM) code ABAQUS®. In this case each stage of the acquisition chain is considered individually.

In this paper, once we validate our FE Model for wave propagation, we study the effects of the geometry, of the type of sources and finally of the sensor.

## 2 MODEL VALIDATION

For obvious reasons, we first perform validation tests of the FE model by comparing experimental and numerical results. In the experimental setup, pencil lead breaks are introduced onto the surface of aluminium specimens having three different shapes shown in Figure 1, the thickness for all specimens being 3.7 mm. The EPL16 specimen has the exact shape of the dumbbell test pieces typically used in the laboratory for material characterisation in general and AE tests in particular. Other shouldered test bars EPL3 and EPL80 were especially designed to mimic the behaviour of a thin rod and a plate respectively, for which analytical solutions of guided propagating modes are easily calculable. The signals are detected by means of a laser vibrometer, which measures the out-of-plane velocity on a surface point. Here we have not used a piezoelectric sensor in order to avoid its effect on the signal waveform, in particular the so-called aperture effect, so that we can isolate the signal recorded from the transformations due to the sensor.

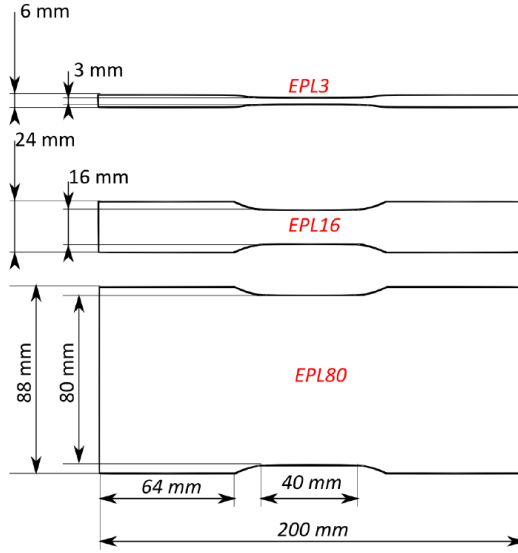


Figure 1: The three Aluminum geometries (EPL3, EPL16, and EPL80) used in all studies of this paper

Concerning the FE modelling, loads by the pencil lead breaks are modelled as displacement sources according to [3]. A 3D geometry has been built for each specimen (EPL3, EPL16 and EPL80), where the material is considered homogeneous, isotropic and perfectly elastic (Young modulus = 180GPa, Poisson ratio = 0.49 and density = 2170 kg/m<sup>3</sup>), the damping is taken into account by Rayleigh parameters. The dumbbells have been meshed with 3D hexagonal C3D8R elements. The average size of one element respects the following criterion:

$$l_e = \frac{\lambda_{\min}}{R} \quad \text{with} \quad \lambda_{\min} = \frac{C_R}{f_{\max}} \quad (1)$$

Where  $C_R$ : the Rayleigh wave speed in the material,  $f_{\max}$ : the maximum frequency, which is usually set at 1 MHz in AE,  $\lambda_{\min}$ : the minimum wavelength and  $l_e$ : the average size of one element. The resolution parameter R was set to 10 for the elements located around the source, to 6 in the gauge section and to 4 in the shoulders.

The measured velocity has been compared to the simulated out-of-plane velocity, a good agreement is observed between the two curves for each case as shown on Figure 2. The green lines indicate the time at which oscillations of simulated signals start, while the red lines indicate the time up to which experimental and simulated signals are comparable.

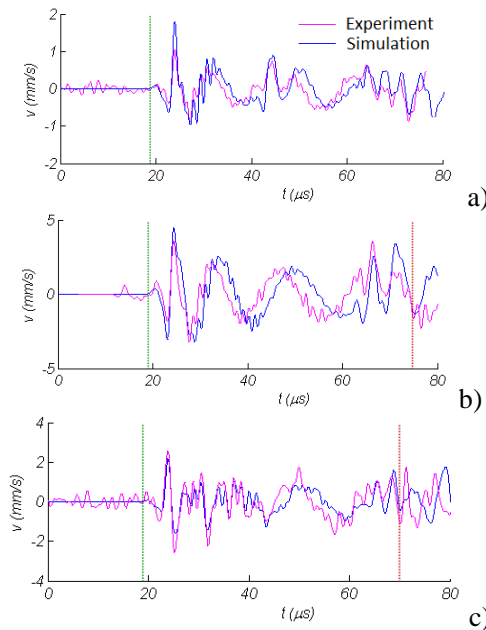


Figure 2: Simulated and experimental velocity : a) EPL80 specimen, b) EPL3 specimen, c) EPL16 specimen

This validation allows us to use the model of propagation medium for other numerical studies. So the next point treated in this paper is the impact of the geometry on the recorded waveform.

### 3 EFFECT OF GEOMETRY

In the three geometries (EPL3, EPL16 and EPL80), the same displacement history (with a chirp signal showed in Figure 3) is introduced on the surface in order to rather equally stimulate all frequencies up to 1.2 MHz. This simulation allows us to identify the different modes of propagation by presenting the 2D Fast Fourier Transform (FFT2D). Those simulated modes are compared to theoretical modes calculated for plates and beams in the case of EPL80 and EPL3 specimen respectively.

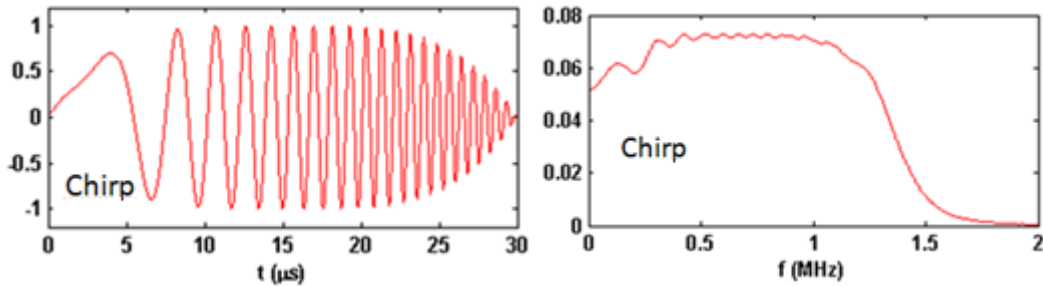


Figure 3: the Chirp source in terms of time and frequency

The results are presented as 2D Fast Fourier Transform shown in Figure 4; this way to present the results allows us to identify the excited modes so that we can compare the simulated results to theoretical calculation. Here the results show that the propagation medium geometry affects the propagated signals. Knowing that, in these geometries, the signal propagates only following specific modes, we deduce that for the large specimen (EPL80) the plate modes are stimulated, while for the thin one (EPL3) the beam modes are stimulated. In the intermediate specimen (EPL16), for which the FFT2D is more complex, and the identification of modes is practically impossible: this geometry cannot be assigned neither to a plate nor to a beam.

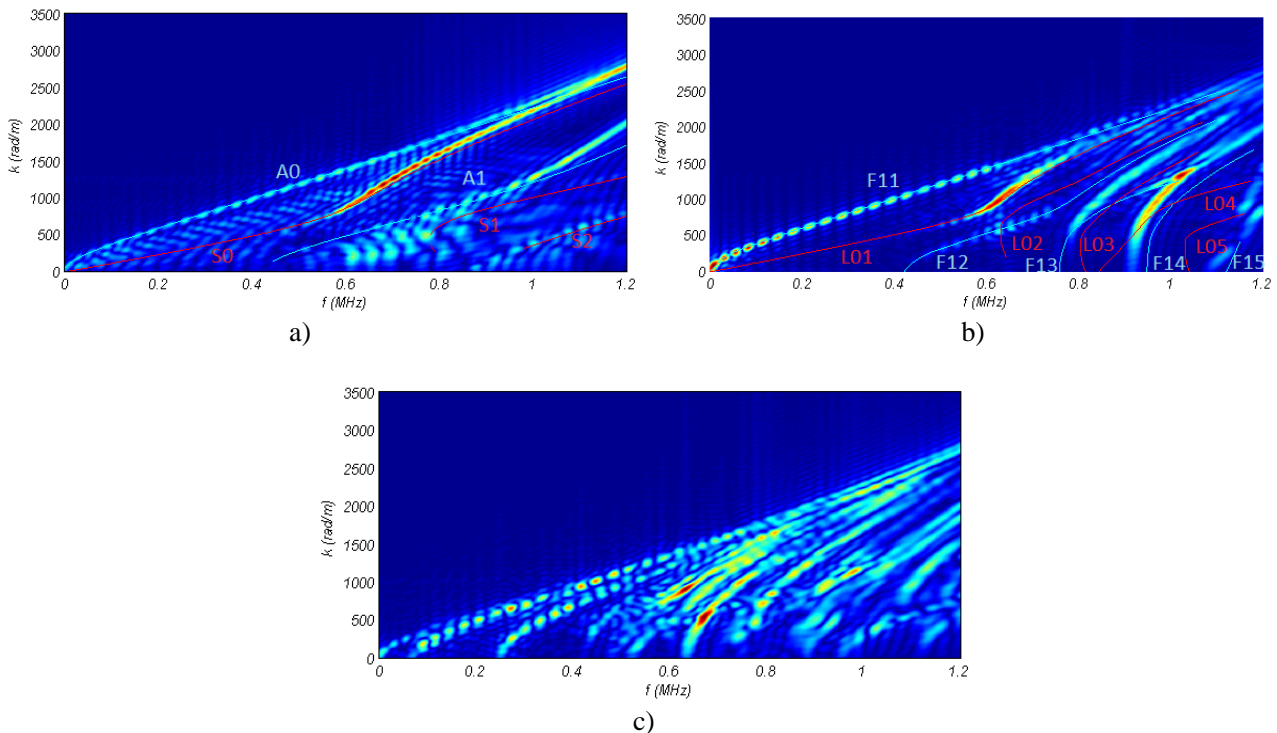


Figure 4: FFT2D for the three geometries excited by the same source simulated on the surface, a) the large specimen (width = 80mm), b) the fine specimen (width=3mm) and c) the medium specimen (width=16mm)

This study shows us that AE tests done on a classical specimen e.g. EPL16 (Figure 1) in the laboratory cannot replace an industrial case from a geometry perspective.

In the following part, we will study the effect of the type of source on the recorded signal.

#### 4 EFFECT OF TYPE OF SOURCES

In this part, we are interested in simulating physical sources. Three sources corresponding to three different damage mechanisms have been modelled as buried point sources, according to [4], in three identical specimens (of equal thickness = 3.7 mm). The sources are located in the gauge section, in the median plan and the centre of the specimen width. They are modelled as dipole forces as shown in Figure 5, representing the expansion, fracture in-plane shear mode and the fracture-opening mode. The sources rise time is  $1\mu\text{s}$ . the particle velocity is calculated on the section of the specimen from the epicentre to its end. The results are presented in the form of FFT2D (wave number in terms of frequency).

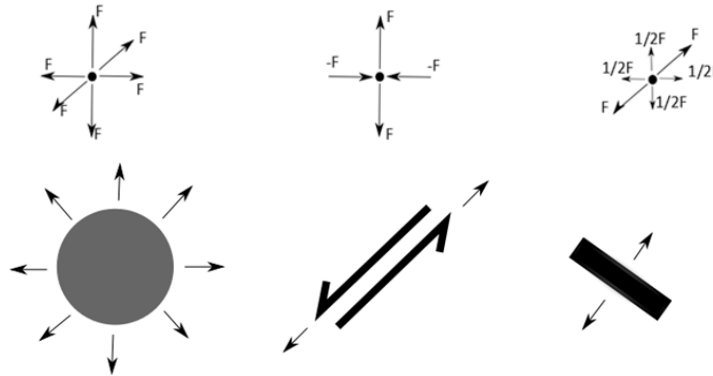


Figure 5: The modeled sources: expansion, fracture in-plane shear mode and the fracture-opening mode

The Figure 6 shows the FFT2D results for the different types of damage. The stimulated modes are not the same in the three cases neither the stimulated frequency range. These results highlight an acoustic signature for each kind of source.

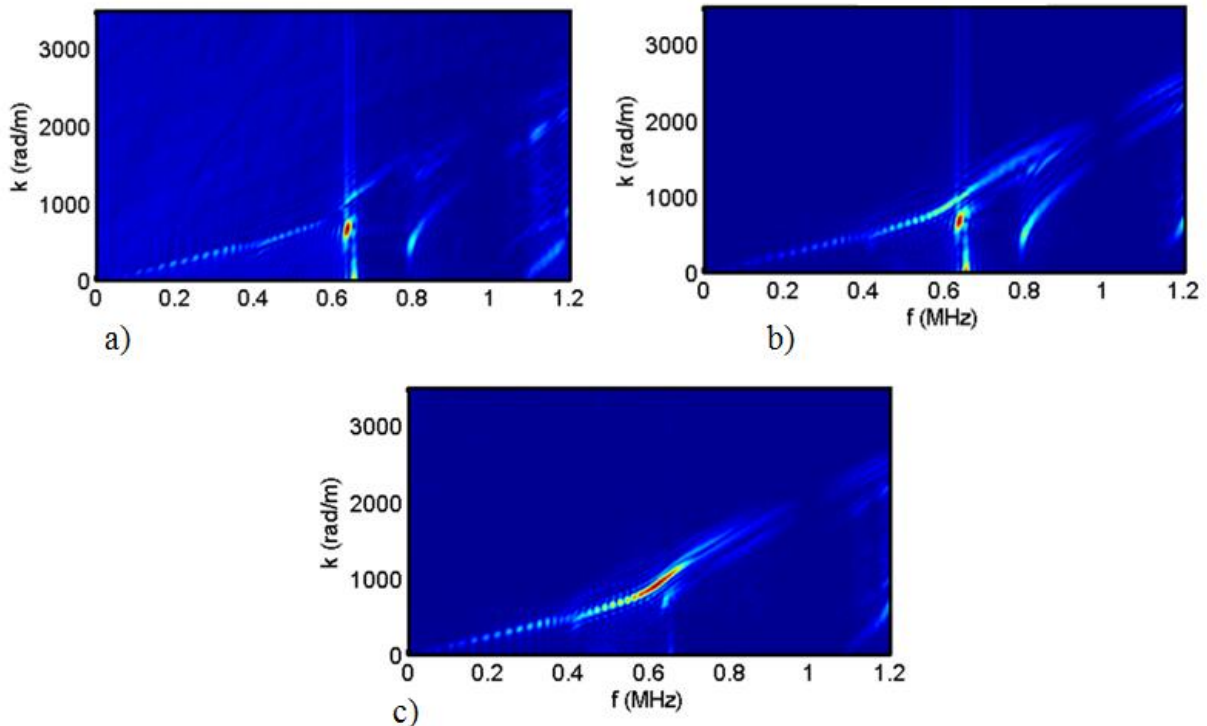


Figure 6: FFT2D of the same geometry stimulated by different type of sources; a) expansion, b) fracture in-plan shear mode and c) fracture opening mode

All studies above are done without considering the piezoelectric AE sensor. This latter, depending on its type, is known by having resonant frequencies and limited bandwidth. So, in the last part we will take into account the sensor effect on the recorded signals.

## 5 EFFECT OF PIEZOELECTRIC SENSOR

The last study in this paper concerns the effects of the sensor on the signals. The strategy is to study the AE signals without considering the sensor, then adding the sensor effect and compare results. The results without sensor are based on simulation results. The sensor is taken into account by its transfer function experimentally determined by the reciprocity method [5]. This transfer function is added in the post-processing phase in the Fourier domain, following the equation 2:

$$S_{sensor}(f) = M(f) \times S_{surf}(f) \quad (2)$$

Where  $S_{sensor}(f)$ : the signal spectrum,  $M(f)$ : the sensitivity function and  $S_{surf}(f)$ : the spectrum of the simulated signal retrieved from the surface representing the sensor's sole at the sensor position.

In this part, the analysis is based on a traditional study of AE signals i.e. descriptor analysis. To obtain several AE signatures as results, different kind of sources and different geometries are considered.

- Sources (Figure 7): the fracture opening mode (S1) and fracture in-plan shear mode (S2)
- Geometries (Figure 1) : EPL3, EL16 and EPL80

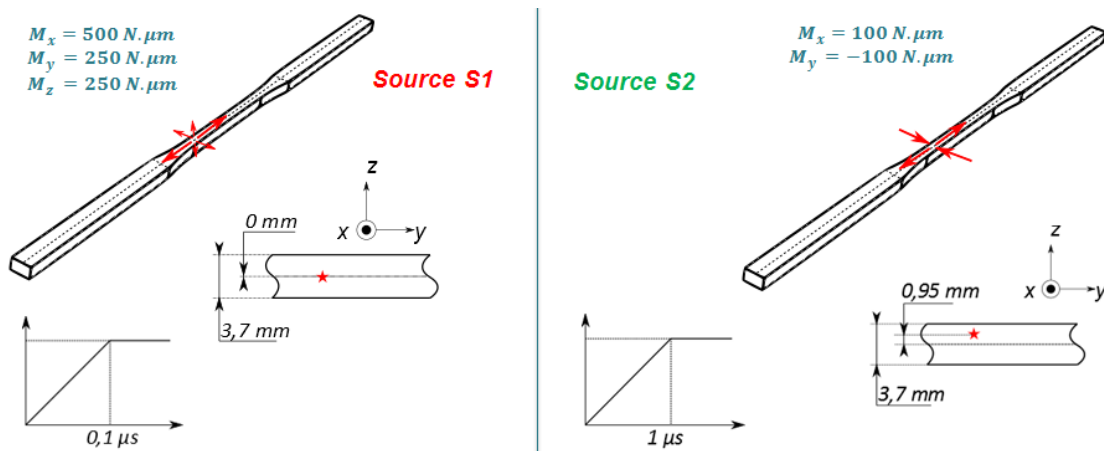


Figure 7: Sources S1: fracture opening mode and S2: fracture in-plan shear mode applied to the three geometries

In order to have a good EA descriptors analysis, we selected relevant descriptors. The criteria for this selection are:

- the descriptor is constant regardless of the distance from the source
- it is independent of specimen geometry
- its value depends on the characteristics of the source

Based on those criteria, the pertinent descriptors selected are the zero-crossing rate (temporal descriptor) and frequency centroid.

The left panel in Figure 8 – left shows the results of classification in terms of the pertinent descriptors without sensor. We can clearly identify two classes. Each class is assigned to a different source. However the right panel of the same figure shows the results of classification after considering the sensor (in this case: a typical commercial PAC $\mu$ 80 sensor from Euro Physical Acoustics). We observe an overlapping of classes, which highlights the transformation of classification results due to the piezoelectric sensor.

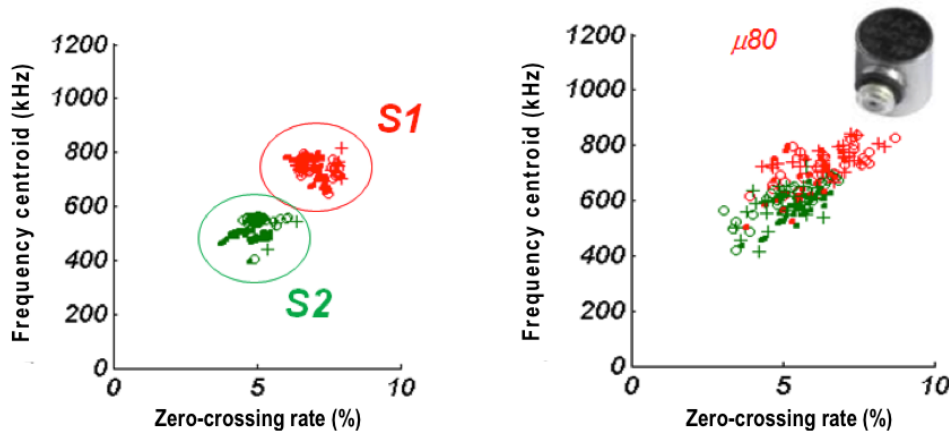


Figure 8: Classification result without considering sensor (left panel) and after considering the  $\mu$ 80 sensor effect (right panel)

Finally, this last result presents what we see in our screen as recorded signal when using sensor but the result without sensor presents what kind of improvement in terms of clustering could actually be obtained when deconvolving the sensor effect on the signals.

## CONCLUSIONS

The aim of using the modeling of AE is to understand the transformations of the signal from the source to the acquisition system. Firstly, comparing simulated results to experimental ones validates the propagation medium model. Then the model is used to study the effect of the geometry, the effect of sources and the effect of sensors. Each of these parameters has its own intervention on the signal and this paper showed how its affect the recorded signals.

This paper basically treats the case of isotropic homogenous material. It is considered as a first step in the modeling of Acoustic Emission, before addressing the problem of anisotropic materials. The modeling of AE in composite material is ongoing in view of its significance to understand the different type of sources generally observed during the degradation of such more complex materials.

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