

On modelling techniques for the numerical simulation of Acoustic Emission signals

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Abstract

Acoustic Emission (AE) is a highly sensitive technique for detecting the initiation and evolution of damage in materials, widely used in structural diagnosis and health monitoring. However, its sensitivity results in large datasets, making it essential to distinguish damage-related signals from environmental noise and other unrelated acoustic events. In practice, experiments conducted under fully controlled conditions, where specific damage mechanisms such as micro-crack initiation or fibre breakage can be directly correlated with recorded AE signals, are often extremely difficult or impossible. In this context, numerical simulations provide valuable support. A reliable numerical model enables the simulation of individual damage events and the prediction of the corresponding signals detected by AE sensors. Developing such models is challenging, as they must capture the entire physical chain: (i) elastic energy release due to locale sub-critical crack formation and / or propagation, (ii) wave propagation through the material, particularly including damping, (iii) transmission of surface vibration to the sensor, (iv) piezoelectric conversion of mechanical vibrations into electrical signals, and finally (v) signal processing into the amplitude-time-frequency representation, typically expressed in decibels (dB). This contribution presents recent advancements achieved by our team, in the development of numerical tools capable of addressing these challenges.

Keywords: Acoustic Emission, Structural Diagnosis, Numerical Modelling, Elastic Wave Propagation, Fracture Detection

1. Introduction

Acoustic Emission has become an established technique for the detection and monitoring of damage in engineering materials and structures [1]. Owing to its high sensitivity to the release of strain energy, AE enables the identification, in metallic and various materials, of early-stage damage mechanisms such as micro-crack initiation, crack propagation, localised plastic deformation, and fibre breakage, specifically in composite materials. This capability makes AE particularly attractive structural diagnosis applications, where the early detection of degradation is crucial for ensuring structural integrity and safety [2].

Despite its advantages, AE monitoring presents significant challenges. The high sensitivity of the method results in large volumes of recorded data, often containing contributions not only from damage-related mechanisms, but also from other sources, like frictional effects, boundary interactions, and other acoustic sources which are of no particular interest regarding structural integrity assessment. Discriminating between relevant and non-relevant signals remains a major issue, particularly in complex structures operating under realistic service conditions. Moreover, controlled experimental setups that allow a one-to-one correlation between a specific damage event and a measured AE waveform are difficult to achieve, especially in heterogeneous or large-scale systems. Within such a framework, numerical modelling (e.g. by the Finite Element Method) represents a powerful complementary approach (see, e.g., [3]). By simulating specific established damage mechanisms, under controlled pseudo-experimental conditions, numerical methodologies



can help establish a direct relationship between physical damage events and the corresponding AE response signals. However, accurately reproducing AE signals is a highly complex task, both from a theoretical and a computational viewpoint, since the signal source definition and propagation [4], and in possible interaction and friction behaviours (see, e.g., [5]), toward a diagnosis approach (see, e.g., [6]). Consistently, a suitable numerical modelling toward the assessment of Acoustic Emission signals requires the consideration of the complete chain of coupled physical phenomena, from energy release at the damage source, to signal acquisition and processing. The present work contributes to this effort by the implementation of numerical model capable of reproducing these processes in a consistent and physically grounded framework, particularly focusing on signal generation related to crack propagation and signal wave propagation affected by material modelling.

2. Numerical methodology

The proposed methodology aims at reproducing the full physical sequence, heading from a localised damage event, within a structural component, to the final AE signal assessment, as provided by acquisition systems. The modelling framework could be structured into five main stages.

(Stage i) First, the damage event is represented through an appropriate source model describing the release of elastic energy within the material. Depending on the considered mechanism (e.g., micro-crack formation, crack extension, or fibre rupture), the source is characterised by a specific numerical approach. This formulation allows the controlled definition of source location, orientation, temporal evolution, and energy content. In particular, in the present work, two approaches are considered for the fracture initiation and propagation, namely by a stress annihilation procedure and by cohesive finite element modelling [7]. Comparison results of such simulations are shown in Fig. 1, where the other model parameters are kept unchanged.

(Stage ii) The propagation of elastic waves generated by the source is simulated using finite element discretization with explicit time integration. The governing elastic-dynamic equations are solved within the material domain, accounting for its geometry (although focusing on the region of interest), boundary conditions, and mechanical properties. In the current research, among the material constitutive properties, the damping behaviour is deemed highly significant and relevant to the AE signal propagation. Therefore, starting from a classic modelling approach [8], a Rayleigh description is adopted:

$$\mathbf{C} = \alpha \mathbf{K} + \beta \mathbf{M} \quad (\text{Eq. 1})$$

where, $\mathbf{C}$, $\mathbf{K}$ and $\mathbf{M}$ are, respectively, the damping, stiffness and mass matrices, while α and β are damping parameters. The gathered signal responses are represented in Fig. 2, comparing an undamped material description with two reliable sets of damping parameters.

(Stage iii) The interaction between the propagating waves and the AE sensor is modelled, considering the measurement of surface displacement component, velocity component or contact pressure from the structural component to the sensor interface. This stage ensures that the mechanical perturbation reaching the sensing element is realistically represented. (Stage iv) The piezoelectric response of the sensor could be assessed, as transferred from the mechanical input at the sensor surface into a converted electrical output signal. (Stage v) Finally, the simulated electrical signal is processed to reproduce the amplitude-time-frequency representation, typically generated by AE acquisition systems, and converted into decibel (dB) output response, for sake of comparison and validation with experimental data.

The present work focuses on the first two stages of the devised process, highlighting the intrinsic physical and numerical level of complexity. In particular, the computed results, as plotted in Figs. 1 and 2 display the major trends assessed by the proposed various approaches and parameters adopted in the modelling strategies.

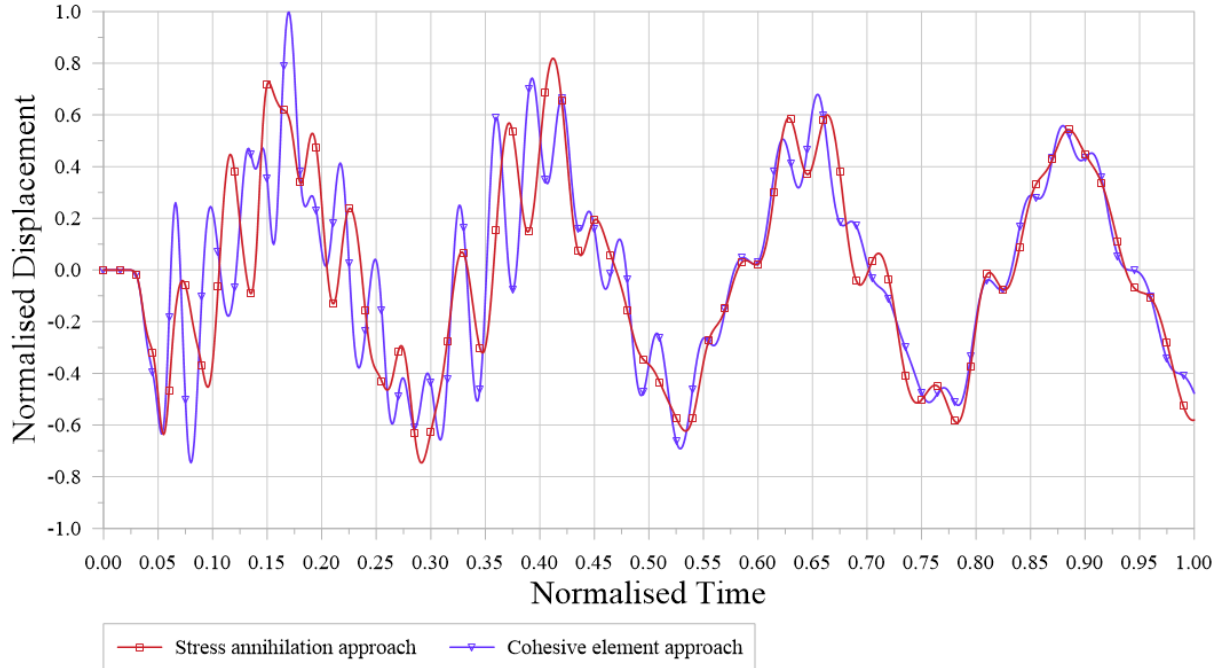


Fig. 1. Surface vibration (displacement) response signal, at AE sensor measurement point, upon two different crack propagation approaches.

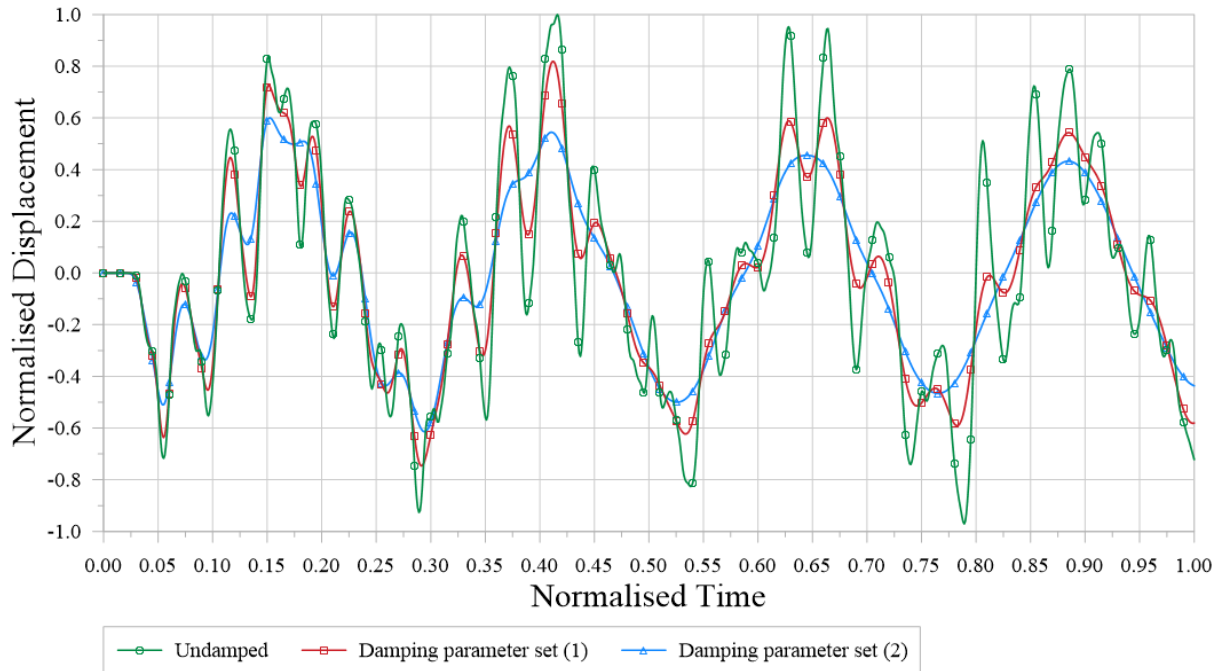


Fig. 2. Surface vibration (displacement) response signal, at AE sensor measurement point, as affected by material damping modelling.

3. Closing remarks

This work devises a comprehensive numerical framework for the simulation of Acoustic Emission signals, generated by various localised damage events, in metallic structural components. By reproducing the complete physical chain, from elastic energy release to the final AE signal

representation, the proposed approach enables a physically consistent interpretation of AE measurements. The integration of source modelling, elastic-dynamic wave propagation, and sensor-measurement methodology provides an investigation, and possibly identification, tool in which the influence of individual parameters can be systematically investigated. Such a framework offers significant potential for improving the interpretation of signal responses and the reliability of AE-based damage identification. In particular, it supports the establishment of clearer correlations between specific damage mechanisms and their corresponding signal features, helping to reduce uncertainties associated with noise, complex geometries, and material heterogeneity. Although further step in delving the numerical process and the validation against experimental data can be required, the present advancements represent a meaningful step toward predictive, computationally-assisted analyses of Acoustic Emission methodologies for structural diagnosis applications.

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