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A novel multi-segment path analysis based on a heterogeneous velocity model for the localization of acoustic emission sources in complex propagation media

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A B S T R A C T

In acoustic emission analysis, common source location algorithms assume, independently of the nature of the propagation medium, a straight (shortest) wave path between the source and the sensors. For heterogeneous media such as concrete, the wave travels in complex paths due to the interaction with the dissimilar material contents and with the possible geometrical and material irregularities present in these media. For instance, cracks and large air voids present in concrete influence significantly the way the wave travels, by causing wave path deviations. Neglecting these deviations by assuming straight paths can introduce significant errors to the source location results. In this paper, a novel source localization method called *FastWay* is proposed. It accounts, contrary to most available shortest path-based methods, for the different effects of material discontinuities (cracks and voids). *FastWay*, based on a heterogeneous velocity model, uses the fastest rather than the shortest travel paths between the source and each sensor. The method was evaluated both numerically and experimentally and the results from both evaluation tests show that, in general, *FastWay* was able to locate sources of acoustic emissions more accurately and reliably than the traditional source localization methods.

1. Introduction

Health condition assessment of existing structures is becoming more and more of a necessity in order to provide well-informed decisions about maintenance and repair. The need for noninvasive health monitoring techniques and nondestructive testing methods is therefore essential. Acoustic Emission (AE) analysis has been accepted as one of the most effective nondestructive methods among the NDT society due to its potential in fast and efficient assessment of damages in materials and structures. A growing interest in this technique and its potential for the use in the nondestructive evaluation of materials and structures has been shown since Joseph Kaiser [1] published his pioneering PhD work in 1950. This interest, both from academia and industry, has gained the technique a wide acceptance in the world and a momentum in use in myriad of applications. One primary and fundamental step in acoustic emission analysis is the location of the sources of emissions which represent an indication of where a sudden release of energy (due to internal stress redistributions) is happening. In structural concrete, the sudden release of energy is primarily related to the opening and propagation of cracks. Therefore, revealing the locations of these cracks can be achieved by locating the sources of acoustic emissions.

Many algorithms, methodologies and techniques for locating sources of acoustic emissions have been developed and implemented in different applications. One technique that has received a particular interest and has been widely used in source location problems is based on an algorithm developed by Geiger in 1910 [2]. A detailed summary of this technique and of other traditional source localization algorithms can be found in [3,4]. The vast majority of these techniques rely on two main assumptions: (1) homogeneous velocity models where the elastic wave velocities are assumed to be constants and (2) straight wave paths between the source and the AE sensors. These assumptions represent a major drawback as each technique is unable to consider both the effects of heterogeneity of the material and the presence of geometrical irregularities (e.g. cracks) on the wave paths. Therefore,

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the use of such location algorithms with heterogenous complex media usually results in considerable source location errors.

To allow for heterogeneity and geometrical irregularities, some signal-based source localization methods, such as Time Reverse Modeling have recently been introduced [5,6]. Some probabilistic approaches that account for the variability of input (e.g. wave speed) as well as other source location parameters have also been proposed [7–9]. These methods have shown certain degrees of success, however, are usually complex and require considerable computational effort. A good summary of numerous other Acoustic Emission source localization (ASL) methods applied on isotropic, anisotropic and complex materials is presented in an interesting article by Kundu [10]. The advantages and disadvantages of each technique are also highlighted and discussed. Moreover, Kundu et al. [11] proposed, very recently, an advanced two-step hybrid technique for accurately localizing acoustic source in anisotropic structures, using sensor clusters. The advantage of this proposed technique compared to all other ASL methods is that it does not require any knowledge about the material properties of the heterogeneous propagation medium. Due to the lack of similar innovative methods, the literature still shows that the Geiger-based method, although well suited for homogeneous non-cracked materials, is extensively applied for heterogeneous materials [12]. This highlights the need for more reliable source location methods that are able to consider the effects of heterogeneity and geometrical irregularities on the wave propagation path. For this purpose, a novel source location method, called *FastWay*, capable of incorporating the aforementioned effects, is presented and discussed in the present paper. Firstly the problem description is outlined and the principle objective of this research is highlighted. Secondly, a general overview of the traditional Geiger's location method and its applications for both homogeneous and heterogeneous materials is provided. The reason this method is discussed is to draw a direct comparison between its source location performance and the location performance of *FastWay*. Thirdly, an in-depth description of the proposed location scheme *FastWay* is given and its concepts, fundamentals, advantages and limitations outlined. Finally, the results of both a numerical and an experimental studies conducted with the aim to investigate on the capabilities of *FastWay* in locating sources of acoustic emissions in heterogeneous cracked media, are presented and discussed. The proposed scheme could be applied to locate sources of AE in different materials. In this study, however, structural concrete was the material of particular interest.

2. Problem description and objective statement

2.1. Problem description

Concrete, probably the most widely used construction material worldwide, is a heterogeneous material that is prone to fissures and cracks due to mechanical, chemical and physical deterioration processes [13]. In structural concrete, cracking starts at relatively low stress conditions due to the low tensile strength of the cement matrix. As a result, the embedded reinforcement, which typically consists of steel reinforcing bars, is activated in order to take over the tensile forces. When cracks occur, elastic energy is suddenly released due to internal stress redistributions. The energy released propagates outward from the source of the crack towards the surface of the structure in the form of elastic body waves. During the journey, these waves take to travel from the source to the surface, many factors that have varying effects on the nature, the amplitudes and the traveling paths of the waves, come into play. Most of the factors are controlled by the material and geometrical complexities of the propagating medium. For instance, the nature of the propagating medium (homogeneous, heterogeneous) and the presence of cracks may considerably affect, depending on the degree of heterogeneity and the size and shape of cracks, the way the elastic wave field travels. For uncracked homogeneous media, the elastic waves travel along a straight path without any interruptions, until it interacts with the specimens surface (see Fig. 2(b)). In cracked and/or heterogeneous materials such as concrete, the waves interact with complex arrangement of constituents (cementitious materials, aggregates, steel bars, etc.) and random distributions of voids and cracks, all with different material impedances. This encounter causes a propagating wave to deviate from a straight path and follow a complex path. In many cases, the wave dies out on the way, before even reaching the surface, due to energy attenuations. The wave is also subjected to different phenomena such as reflection and refraction due to the interaction at the boundaries between dissimilar neighboring materials (e.g. air void and steel) present in the propagating medium. All these factors result in very complex wave propagation paths. Fig. 2(c) presents an illustrative example that shows how a crack (a predefined notch in a concrete specimen) creates new surface boundaries, which reflect the major part of the wave energy. Therefore, it is only possible to detect the wave at the surface if it bypasses the crack. If the specimen is reinforced and the reinforcing bar crosses the crack, the bar, in most cases, will guide the wave through the crack (Fig. 2(d)). It can also be seen that the combination of concrete and steel damps out the amplitude of the displacements due to the scattering of the wave front. The average material properties incorporated in the numerical model used to obtain Fig. 2, are summarized in Table 1.

In conclusion the wave does not follow a straight path in order to propagate from the source to the surface of the structure (in heterogeneous cracked or untracked materials). This is a major problem in acoustic emission source location applications. In fact, in most traditional source location problems, the wave path is assumed to be perfectly straight and the presence of cracks in the propagating medium is often neglected due to the challenging implications of modelling cracks in the wave propagation equations. To account for the deviations on the wave path, one should consider the different aforementioned effects and most particularly the effects of geometrical irregularities (e.g. cracks, air voids).

2.2. Influence of heterogeneity and geometrical irregularities on the propagation of elastic waves

Geometrical irregularities, cracks, air voids, and inclusions with high impedance contrasts (e.g. aggregates, reinforcing bars) have the most significant influence on the propagation behavior of elastic waves. To account for these influences in the numerical model, the outer and inner structure of the propagation medium has to be known a priori. Table 1 lists the different materials of the numerical model used for Section 5.1, along with the corresponding material properties. Due to the high impedance contrast between air and each of the solid materials, the wave velocity in air was simplistically assumed to be equal to zero. In fact, less than 0.01% of the elastic energy is transmitted each time the wave hits a solid-air boundary [15]. As a result, all the areas filled with air were considered to be "roadblocks" that prevent further propagation of the wave.

In the presence of a propagating wave, the path is commonly assumed to be straight (l_d in Fig. 1). However, since it is assumed that no elastic energy is transmitted through air voids, the wave has to bypass these roadblocks on its way, l_{bp}, to the recording sensor. In case of (small) air voids, the deviation from the straight path ($l_{bp} - l_d$) is marginal compared to the straight distance l_d between source and sensor. The influence of air voids on the fastest wave