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3D reconstruction of cracks propagation in mechanical workpieces analyzing non-stationary acoustic mixtures

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A B S T R A C T

Cracks are one of the main causes of solid bodies weakening and are a hidden threat for mechanical systems. Acoustic emission is an indicator of cracks initiation and propagation and is widely exploited for the localization of cracks in non- or weakly-transparent environments. The present study enriches the functionality of multiple existing algorithms in crack localization using acoustics. The novelty is in the reconstruction of the complex geometry of the crack path and tracking its propagation in time, whereas existing methods focus only on the localization of the crack without any information about its geometry. The algorithm uses sparse acoustic signal representations as relative energies of the narrow frequency bands, extracted with the *M*-band wavelet transform. Non-linear independent component analysis is applied to de-mix the recorded acoustic signals into a number of separate acoustic patterns. Furthermore, a triangulation, using the time delay arrivals, is applied for each of such patterns separately, thus extracting multiple individual emittance sources. The algorithm was tested using synthetic data that replayed various scenarios of crack propagation together with different detector arrays configurations and its behavior was analyzed. Additional verification with real-time data was carried out by analyzing signals from crack propagation in glass along a known programmed path. The acoustic data was recorded with four fiber Bragg gratings. In both cases, the algorithmic framework showed a high efficiency in recovering the geometrical configuration of the crack.

1. Introduction

The diagnosis and prevention of the catastrophic failure of workpieces in mechanical systems is a critical task in fracture mechanics and is of utmost importance in numerous applications [1]. The nature of cracks is caused by a release of locally accumulated mechanical stresses that exceed the fracture toughness (Kc) of the material. The exact distribution of those stresses inside a material is impossible to forecast as their re-distribution in time has a stochastic nature [1–3]. The occurrence of cracks results in the creation of new free surfaces inside a solid medium, which after a certain time reach a critical size and cause a sudden fracture of the material [1,2]. This leads to extensive cost in terms of either damages, delay in production lines or even injury of people [1,2]. For this reason, monitoring of cracks has been in the focus of researchers since the first work of Griffith in this field since 1920 [3]. Despite all the efforts, predicting the location of the crack initiation, direction and velocity of its propagation remains unsolved until today. Consequently, precise diagnostic systems that monitor this process and evaluate the possible damage are required.

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Acoustic emission (AE) is a relevant method for cracks monitoring mainly due to its applicability to non-transparent media and is, nowadays, a standard diagnostic tool in many applications [4–6]. AE derives from elastic waves deformations, generated by the release of the locally stored stresses mentioned above [4]. This nature of AE allows to correlate part of its energy with the induced damages [4,7]. Another advantage of AE is in the possibility to spatially localize the cracks in non-transparent solid environments [7–10]. This information is crucial for many mechanical systems, where the geometrical configuration of the crack propagation path is a key factor in estimating the workpiece lifetime [11].

At present, the existing crack localization methods are mainly based on time delay of arrival (TDA) of the acoustic wave [7–11]. In general, this method exploits the known propagation speed of AE inside the medium and known relative positions of the detectors that are used for further triangulation. Reconstruction of the geometrical configuration of the crack path using TDA is also possible by triangulating the individual patterns, extracted from received AE signals. The usage of the individual patterns also allows to replay the propagation of the crack in the time domain [9,12,13]. However, despite the apparent simplicity, this approach remains a complicated undertaking.

The search of pattern correspondences within several acoustic signals is a non-trivial task. This is mainly due to the distortions in the received signals due to environmental factors, presence of noises and complex mixture of individual AE patterns between each other [12,14]. Several methods for pattern correspondences search exist and they are based on cross-correlation and statistical analysis [7,13,15,16]. The robustness of those methods can be increased by noise suppression in the detected signals [15,16,17], while the environmental distortions can be compensated by solving inverse problems of the acoustic wave propagation inside a medium [12,14,18]. Both approaches may reduce the number of outliers in the pattern correspondences but require a detailed knowledge about the environmental properties and/or noise characteristics, which are not always available. In real life applications, this brings inaccuracies in those algorithms performance in unknown environments. Another constraint of the existing methods is in the reconstruction of the crack propagation path that usually takes place in several directions with individual propagation velocities. In this case, the received signals are complex mixtures of multiple AE patterns with unknown content. Those patterns are produced by an unknown number of cracks sub-paths that have different localization. A mixing of the patterns takes place with random drifts relatively to each other, due to the presence of noise and environmental distortions. Today, no algorithm exists that allow reconstructing the crack path under such circumstances. At the same time, knowing the geometry of crack path is crucial to predict the lifetime of mechanical components [19].The present study is a supplement to existing studies on crack localization that aims to remove the constraints of existing methods, namely: i) operate without prior knowledge on the environment and ii) reconstruct the crack propagation path geometry in case of several propagation directions and track their changes in time. This is achieved by de-mixing the received AE signals into individual patterns using non-linear independent component analysis (ICA).

ICA [20] is a statistical method that aims to decompose a given signal into several sub-components with a maximum independence, relying on the non-Gaussianity in their distributions [20]. As mentioned above, in this study, the received AE signals are considered as mixtures of multiple separate acoustic patterns of non-stationary nature and the objective of ICA applications is to define the mixing law.

The attractiveness of ICA towards the crack initiation and/or propagation monitoring problems is in the possibility to operate on signals without prior knowledge about their characteristics. The released AE from cracks includes information about the local structural degradation that is locally unique [21] and this is a direct task for ICA. In addition, ICA allows compensating the non-linear environmental distortions and noises within a single framework. The known limits of this method are in operating with non-Gaussian probability distributions and impossibility to estimate the order and the variance of the sub-components [20,21]. This causes redundancy in computations so that the usage of ICA is an open topic regarding crack problems. Our motivation for employing ICA in this work was given by the research of Jiao et al. [5]. The authors showed that the AE signal induced by a crack is a mix of several modes that differs from each other in a statistical way and are separable. In Mostafapour et al. [18], it was demonstrated that the signal content and the environmental distortions in the AE possess several unique characteristics that can be differentiated. Therefore, the present work investigates the feasibility of spatial localization of crack initiation and/or propagation employing mathematical tools [20], keeping the physical explanation of the AE content outside the scope of this work.

The article is divided into four sections. Section *Crack initiation/propagation induced AE signals and test datasets* has three sub-sections. The first one describes the particularities of crack induced acoustic signals. The second explains the creation of synthetic dataset (artificial dataset) to check our algorithm. The last describes the acquisition of the real life dataset. The section *Signal processing* incorporates the description of sparse signal representations using *M*-Band wavelets and the ICA method. The section *Results and discussion* presents the tests on both synthetic and real life data and the evaluations of the algorithm. The section *Conclusion* summarizes the main results and findings as well as perspective of future work.

2. Crack initiation/propagation induced AE signals and test datasets

2.1. Crack initiation and/or propagation induced AE signals

Acoustic emission from crack initiation and/or propagation has been investigated in the last several decades and is actively used in a number of field applications [19]. A typical example is shown in Fig. 1, where Fig. 1a is an acoustic emission signal obtained from the crack in Fig. 1b, in which its path is presented. The crack AE signals are typically long tailed and are