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Spatial scanning for anomaly detection in acoustic emission testing of an aerospace structure

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ABSTRACT

Acoustic emission (AE) monitoring of engineering structures potentially provides a convenient, cost-effective means of performing structural health monitoring. Networks of AE sensors can be easily and unobtrusively installed upon structures, giving the ability to detect and locate damage-related strain releases ('events') in the structure. Use of the technique is not widespread due to the lack of a simple and effective method for detecting abnormal activity levels: the sensitivity of AE sensor networks is such that events unrelated to damage are prevalent in most applications. In this publication, we propose to monitor AE activity in a structure using a spatial scanning statistic, developed and used effectively in the field of epidemiology. The technique is demonstrated on an aerospace structure – an Airbus A320 main landing gear fitting – undergoing fatigue loading, and the method is compared to existing techniques. Despite its simplicity, the scanning statistic proves to be an extremely effective tool in detecting the onset of damage in the structure: it requires little to no user intervention or expertise, is inexpensive to compute and has an easily interpretable output. Furthermore, the generic nature of the method allows the technique to be used in a variety of monitoring scenarios, to detect damage in a wide range of structures.

1. Introduction

Acoustic emission (AE) testing or analysis is the name given to the technique of detecting small releases of energy (so called acoustic emissions) within a structure, usually pertaining to microscopic structural changes. The occurrence of energy release is generally caused by some outside loading of the structure: in the laboratory this may consist of some applied fatigue or tensile load to a specimen; where AE is used to monitor a structure *in situ*, the loading consists of the structure's normal service load. The point from which energy is released is known as the *source*, and the energy may arise from a variety of mechanisms including those related to fatigue fractures, tribological phenomena, corrosion, fibre breakage or pullout in composite materials, or a variety of other mechanisms. Strain energy released at the source propagates through the structure as elastic waves: these waves can be detected by transducers mounted on the surface of the structure. The response of the transducer can then be stored digitally for analysis.

In the field of condition monitoring, AE techniques have seen some successes [1–3]. In this case, where AE is used to monitor rotating machinery, the source of AE is continuous. Energy is released steadily as the machinery rotates, and the resulting signal recorded at a surface mounted transducer is stationary. Changes in the signal can be used to detect the

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onset of damage in the system, and monitoring techniques based on the frequency content or power of the recorded signals suffice. Monitoring can be performed by setting a threshold for some feature (e.g. power) extracted from the continuous signal: when the feature exceeds the threshold, damage is implicated.

In the case where large structures are to be monitored for damage using networks of AE sensors, the sources often release energy sporadically, as phenomena such as fatigue crack extension and fretting produce transient waves. This results in a series of short 'burst' signals at the sensors, referred to as hits. The location of the source can often be determined by consideration of the time-of-arrival of signals at different sensors in the network, however, the nature of the source is usually obfuscated by the medium through which the elastic wave has travelled: information about the nature of the source is difficult to extract [4]. Since AE testing involves the use of external loading to the structure, it is inevitable that multiple types of source will be present in any test. It is often the case that damage-related hits are massively outnumbered by those related to other sources, such as rubbing and fretting at joints.

Determining the nature of an AE source has been the subject of much research [5–7], and is an important goal, since knowledge of the nature of the source relating to each individual hit would allow the identification of damage in testing environments where other sources are common. As yet, there remains no universal mechanism for source characterisation, although optimisation-based inverse methods of the form described in [8] show some promise. For the purposes of this paper, the source of interest is associated with crack propagation; however, the method described here does not depend on the detailed physical nature of this source i.e. the temporal structure of the initiation event. For this reason, the method does not depend on a knowledge of the fracture mechanics of crack extension; it depends only on the ability to identify the appearance of a new source against an established background. This is the essence of novelty or anomaly detection.

In this publication, a method is proposed for identifying damage in an AE-monitored fatigue test based upon a spatial scanning statistic. Having observed that damage identification is possible in a condition monitoring scenario, using only power received at a sensor, the proposal involves simply monitoring the level of AE activity at a fine grid of locations across the structure. Only a sparse sensor network is required, since AE sources can be located using time-of-arrival information. The spatial scan statistic does not attempt to perform source characterisation: it bypasses this idea by simply looking for abnormal levels of activity. It is a novelty detector.

The spatial scan statistic is a prevalent tool in the field of epidemiology [9], and is a key tool in 'syndromic surveillance', where outbreaks of disease are detected by monitoring symptoms of the disease [10]. For example, outbreaks of influenza can be detected by monitoring the sales of over-the-counter flu remedy [11]. The ideas have been widely applied across the medical field, with application to infectious diseases, water-born diseases, and cancer. See [12] for a complete list. Despite the success of the method in these areas, this is the first application to the author's knowledge of a spatial scan statistic in an engineering application.

Spatial scan statistics are particularly suited to the analysis of AE data, where large numbers of data are unrelated to damage. It is important to note that the scan statistic is not 'classifying' the data as such, rather examining the spatial distribution of the data in order to find areas of unusually high activity (which we refer to as a cluster).

This publication proceeds as follows. The next section introduces the spatial scan statistic with an explanation of the mathematical derivation. The following section discusses issues specific to the scanning of AE data. We then present the setup of a large scale laboratory test of an aerospace component which is to be the subject of the scan statistic, and present the results thereof.

2. Scan statistics

The first work on a general 2D spatial scan statistic was presented by Kulldorff [13]. Previous work had considered only 1D cases, or had used somewhat limited scanning models [14,15]. Kulldorff's presentation was far more general, allowing to search for clusters of various sizes and geometries. Further, the presented method had the important property that the detection of a cluster was not dependent on the configuration of data outside the cluster, making it a powerful statistic in detecting the *location* of clusters, as well as their presence.

The initial methods presented were based on the principle of a likelihood ratio, and p-values were computed using Monte Carlo sampling. Recently, Neill and Cooper [16] presented a Bayesian scan statistic. The use of a conjugate prior led to tractable integrals and a significant reduction in computational requirement as compared to previous work. The work was consolidated in [17], and extended to work with multiple streams. The following explanation of the statistic follows the nomenclature of [17] (see also Table 1) and we also choose to utilise the Bayesian methodology due to its reduced computational requirements and the ease of interpreting the results. Our presentation of the statistic is somewhat simplified, since we are not dealing with multiple data streams.

Consider a series of geographical locations (post-codes, cities, counties—the choice is ambiguous for the moment) which can be indexed by i. Each location has a population b_i, which are at a risk q of exhibiting a certain symptom; the prevalence of which is to be monitored. Under this model, during a fixed time window t the number of occurrences of the disease (the 'counts') at any location c_i is distributed according to the Poisson distribution:

$$p(c_i|b_i,q) = \mathcal{P}o(c_i|qb_i) = \frac{qb_i^{c_i}e^{-qb_i}}{c_i!} \tag{1}$$