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Enhanced damage localization for complex structures through statistical modeling and sensor fusion

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ABSTRACT

Ultrasonic guided waves represent a promising technique for detecting and localizing structural damage, but their application to realistic structures has been hampered by the complicated interference patterns produced by scattering from geometric features. This work presents a new damage localization paradigm based on a statistical approach to dealing with uncertainty in the guided wave signals. A bolted frame and a section of a fuselage rib are tested with different simulated damage conditions and used to conduct a detailed comparison between the proposed solution and other sparse-array localization approaches. After establishing the superiority of the statistical approach, two novel innovations to the localization procedure are proposed: an approach to sensor fusion based on the Neyman–Pearson criterion, and a method of constructing simple models of geometrical features. Including the sensor fusion and geometrical models produces a substantial improvement in the system's localization accuracy. The final result is a robust and accurate framework for single-site damage localization that moves structural health monitoring towards practical implementation on a much broader range of structures.

1. Introduction

Within the paradigm of structural health monitoring (SHM), there exists a hierarchy of information about a structure's state that may be exploited in order to provide a meaningful diagnosis and thereby make well-informed decisions about performance, maintenance, or operational fitness [1]. The most basic SHM systems provide some form of indication about whether the structure has become damaged, based upon pre-established definitions of the target damage resulting from an operational evaluation of the system. The next question following that of existence is the question of location of the damage. Damage extent and type would then be addressed, finally leading to a damage prognosis assessment, the ultimate goal for practical implementation of SHM systems [2].

In order to begin considering the answers to these questions, a particular inspection technology must be selected based on the parameters of the system to be monitored. In this study, ultrasonic guided waves (UGWs) sent and received by a sparse array of piezoelectric transducers are the mechanism for extracting damage information. Sparse array techniques can provide excellent coverage area per sensor, thus offering cost and weight savings over methods utilizing denser configurations [3]. In this paper, UGW interrogation is applied to testbeds of significant geometric complexity, including bolted connections, through-holes, stringers, boundaries, and other geometric features. One of the chief difficulties with

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UGW interrogation has been that any geometric feature causes the waves to scatter (often in a manner similar to a target defect). The resulting multitude of reflections often creates complex, multi-path interference patterns, making the waveforms difficult to interpret. Techniques specifically developed for problems of a realistic level of complexity are needed for the transition of SHM systems to real-world applications.

The present work focuses only on the damage localization problem, or the second step in the SHM decision hierarchy which assumes that the more basic question "Is damage present?" has been answered affirmatively in a global sense. An optimal approach to the purely damage detection problem has been presented previously for the same testbeds [4]. Therefore, the fundamental objective of this paper is to develop methods that will most accurately predict the location of single-site damage on complex structures given that the damage exists.

In this study, a statistical approach is utilized to determine first-arrival time-of-flight information for sparse arrays on two distinct and geometrically-complex testbeds – a bolted frame structure and a fuselage rib aircraft component. The statistical approach, which was presented previously for a notably simpler structure [5], is extended to the more complex testbeds considered here. The results not only demonstrate the robustness of the approach to specific structure and (simulated) damage types, but also confirm its superior localization performance compared to a representative selection of other localization algorithms in the literature. To further enhance the localization accuracy, two novel techniques are developed and implemented: a sensor fusion approach based on the Neyman–Pearson criterion and a simple modeling approach for the most significant geometric features. The integrated localization approach, considering sensor fusion and modeling techniques, provides excellent localization accuracy for highly-complex structures and represents a significant step toward the implementation of viable SHM systems.

2. Localization strategy

Most sparse ultrasonic sensor arrays in the SHM field utilize the method of delay-and-sum beamforming as the basis of determining the damage location [6–8]. In this method, reflectors are located by launching a pulse into the medium from one transducer and receiving the waveform at another transducer. Through knowledge of the wave velocity, sensor locations, and actuation time, the time of arrival of the first reflected wave packet (or "first arrival") can be translated into the total distance from actuator to reflector to receiver. Most often, it is the residual signal – the signal resulting from a baseline subtraction procedure – that is considered, in order to reduce (ideally, to remove entirely) the influence of the direct arrival between sensors and any reflections from benign structural features. The optimal baseline subtraction procedure is used in this study, as a straightforward technique to also minimize the impact of any changes in environmental condition by subtracting the baseline taken in the nearest environmental state, and thereby localize only damage-related reflections [9].

Because realistic structures tend to be more geometrically complex than a uniform plate, reflected damage signals quickly become obscured by reflections from benign geometric features. While appropriate baseline subtraction can help mitigate the effect of these features, all of the echoes from any damage will likewise scatter from the geometric features, causing the residual signal to become substantially more complicated as well. As a result, many adaptations to the delay-and-sum technique have been proposed. A representative selection of these techniques has been implemented in order to compare the proposed solution with those existing in the literature. The details of each localization algorithm are presented in Section 5.

However, in this work structures with a high level of geometric complexity are specifically targeted. These structures present challenges that lend themselves to a statistical formulation given the uncertainty imposed by the complexity. Therefore, a maximum likelihood estimation (MLE) approach presented previously is used as an "arrival filter" to compute the likelihood that any given point in the time series of a particular sensor pair is the true first arrival point [5]. The key assumptions of this approach are as follows: before the first arrival, the enveloped residual signal may be described by a Rayleigh-distributed random process. After the first arrival (due to the complex, overlapping echoes of waves reflected from the damage), the signal may be described as a Raleigh-distributed random process with a greater Rayleigh parameter. Computing the maximum likelihood estimate of each of the two Rayleigh parameters, a likelihood ratio test can be implemented to describe the likelihood that each time point is the first arrival. Because the maximum of the resulting vector is the predicted arrival point, the output of this filter may then be used in a delay-and-sum procedure to produce a predicted damage location in the structure.

There are some other key assumptions that go into the first-arrival estimation procedure. First, as is common to all delay-and-sum formulations, this approach assumes single-mode propagation. That is, one mode is dominantly actuated and received by the sensor array, and this mode has a known group velocity. The velocity in both of these structures has been estimated from the time of flight of the direct arrivals (without baseline subtraction) and the known distance between sensors. The final values consist of the average of the velocities estimated from all tests and most sensor pairs (excluding sensor pairs too far apart to receive direct arrivals and, in the fuselage rib, those with direct line-of-sight obstructions). The final values obtained are 2120 m/s for the frame structure and 5450 m/s for the fuselage rib structure. This procedure deliberately estimates an "effective" or *in situ* group velocity, which represents the speed at which energy actually propagates between sensors and requires no detailed wave propagation models of the medium. Because in guided wave SHM, the frequency and wave mode are usually chosen to avoid the most highly dispersive situations, using the estimated,