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# Optimal placement of sensors for sub-surface fatigue crack monitoring

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ABSTRACT

This paper discusses the scattering of stress waves by defects in representative aircraft structures with multi-layered construction and geometry variation. The approaches for determining and enhancing the probability of detection of non-surface-penetrating defects in such structures as well as minimising the contributions of multi-layered construction and geometry variation to false indications are presented. The results demonstrate the importance of selecting the appropriate frequency and location of the sensor in monitoring sub-surface defects on these structures. The findings suggested that a computer solution of the problem may be required to determine the optimal combination of frequency and sensor location. This study suggests the possibility of incorporating structural health monitoring into the design of future structures which will constitute a significant leap in the current knowledge base of structural health monitoring.



## 1. Introduction

The potential of stress wave-based structural health monitoring methodologies has been widely explored in recent years. The main driver behind this exploration is the high sensitivities of stress waves to small, surface and sub-surface defects in metallic [1] and composite structures [2]. Moreover, the ability of stress waves to travel over long distances within these structures has greatly increased the potential in detecting defects at locations that are difficult to access. However, the propagation of stress waves in multi-layered structures can be scattered by geometry variations, material inhomogeneities and/or structural defects. It is therefore the aim of this paper to build on this knowledge specifically for the benefit of in situ structural health monitoring (ISHM).

ISHM based on propagating stress waves relies on a network of actuating and sensing piezoelectric elements, which are bonded onto the structure. The issues of "false negatives" and "false positives" are major impediments to the practical application of ISHM. In this paper the terms "false negatives" and "false positives" are identified collectively as examples of information infidelity (INF). While the issue of INF is relevant to all modes of ISHM, this study addresses only stress wave-based methodologies. Researchers have reported on the effects of the governing physics, sensor durability, sensor bond durability and environmental effects on this stress wave-based methodology. For example, the effects of operational environment (e.g., temperature fluctuations) were addressed by Rajic et al. [3]. Hoon et al. [4] have described the impact of sensor bond integrity and sensor durability on INF. Whilst all factors affecting stress wave-based methodologies outlined above are germane to INF, the physics governing the interaction of the measurand to the existence of defects and structural variations is of paramount importance.

Callinan et al. [5] reported on the development of fatigue cracks on the F-111 underwing skin. This report also documented the use of a boron/epoxy doubler to repair the damage region. The fatigue crack was reported to have developed as a sub-surface defect on the inside of the wing and propagated outwards. Since it is not feasible to inspect the inside of the wing skin, nor to apply sensors on the inside surface, the use of in situ acoustic transducers installed on the outer wing surface was considered a viable means of inspection. Lamb waves produced by the transducers would provide the interrogating field. However, Lamb waves are scattered not only by defects, but also by geometrical features like integral stiffeners, which form part of the F-111 wing structure. The work discussed in this paper shall address the issues relating to the detection of this type of sub-surface crack in an aluminium structure. This paper shall also report on the ability to use a stress wave methodology for the monitoring of fatigue crack development when the structure is repaired using a bonded boron/epoxy doubler.

In this paper, the scattering of stress waves by defects or service-induced damage in representative aircraft structures with multi-layered construction and geometry variation is characterised. This knowledge shall be used in the development of a robust structural health monitoring scheme. In addition, the approaches for determining and enhancing the probability of detection (POD)

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[6] of non-surface-penetrating defects in such structures, as well as minimising the contributions of multi-layered construction and geometry variation to INF are demonstrated. In this respect, the work reported on in this paper can lead to the removal of this impediment which will constitute a significant leap in the current knowledge base of structural health monitoring.

This study is organised as follows: The models used for the investigation as well as the process of determining INF and POD are described in Section 2. Section 3 reports the results of a series of computational investigations to determine the effects of the presence of sub-surface defects on the propagation of stress waves in a flat plate and in a structure with geometry variations. The results highlighted the importance in the appropriate characterisation of the time (i.e., frequency) scale and length scale of the problem prior to the establishment of an appropriate ISHM strategy. This can help in minimising or elimination of the occurrence of false indications.

## 2. Methodology

### 2.1. Model

Whilst focusing on the problems described by Callinan et al. [5] a series of investigations using finite element analyses have been conducted to determine the effects of:

(1) the presence of the sub-surface defects on the propagation of stress waves,
(2) the presence of geometry variations (including a sub-surface defect) on the propagation of stress waves, and
(3) the presence of geometry variations (including a sub-surface defect) and repair patch on the propagation of stress waves.

To achieve these aims, a series of models were considered. Firstly, a model of an aluminium flat plate (Model #1) was considered. A series of sub-surface defects were introduced in the model. The primary purpose of this model is for demonstrating the interaction of sub-surface defects with the impinging stress wave. In this second model, an aluminium plate with geometry variations was considered (Model #2). The series of sub-surface defects included in the first model were also induced in this model. These analyses will highlight the interaction of the impinging stress wave with the geometry variations and the sub-surface defect. In the third model (Model #3), a boron/epoxy doubler was introduced to Model #2 to simulate a bonded structural repair.

A schematic of the cross-sectional view of the models used for these three cases are shown in Fig. 1. Model #1 is a flat aluminium plate of dimensions $3.6\ \text{mm} \times 100.0\ \text{mm} \times 140.0\ \text{mm}$ and the $3.6\ \text{mm} \times 140.0\ \text{mm}$ face is shown in Fig. 1. The isometric view of the model with geometry variation (denoted as Models #2 and #3), is shown in Fig. 2. This represents the lower wing skin of the F-111. Fig. 3 shows the finite element model of the structure shown in Fig. 2 and the region where the data are extracted for analyses. The mechanical properties of the materials used in the finite element analyses are reported in Table 1.

To simulate the development of a sub-surface defect in the underwing skin, notches of three different sizes are used, namely 33%, 67%, 100% (representing penetration of the skin) were used. The profile and dimensions of these notches are shown in Fig. 4 and Table 2, respectively. The excitation used is shown in Fig. 5. This pulse has a wide frequency bandwidth. The results presented in this paper shall be analysed within a bandwidth of 100–600 kHz. Within this frequency bandwidth, it is expected that a number of Lamb wave modes are excited. The propagation of the Lamb wave modes shall be analysed from the displacement field calculated resulting from the pulse input.

### 2.2. Probability of detection

Probability of detection (POD) is often used in non-destructive inspection procedures. The POD of an NDI methodology to detect a given defect size is dependent on several parameters including device placement, operator, surface conditions and couplant [7]. In the case of ISHM, the sensor placements and surface conditions are pre-determined and do not change with time. There is also no issue with change in operator. In this respect, the term "probability of detection" (POD) used for ISHM should be different from that of traditional NDI and shall first be defined. In the monitoring methodology proposed in this paper, as in many others, the change in the received signal with respect to the "undamaged" case is used as an indication of the development of a defect. In this respect, we firstly assume that there is a probability of 1 when, for a given defect size, the received signal is reduced by 90% of its initial "undamaged" value. A probability of 0 is assumed when the change in the received signal is reduced by 10% or less. For the purpose of this investigation, in order to demonstrate the concept of POD, we shall assume a linear variation in the probability in the intermediate levels of received signal reduction. Using this definition of POD, it is envisaged that the spatial variation in the POD calculated can be used as a guide for optimal sensor location. In this respect, the optimal sensor location shall reside in regions of maximal POD.

In this following analysis, the changes in the amplitude of the stress wave resulting due to the presence of a defect shall be

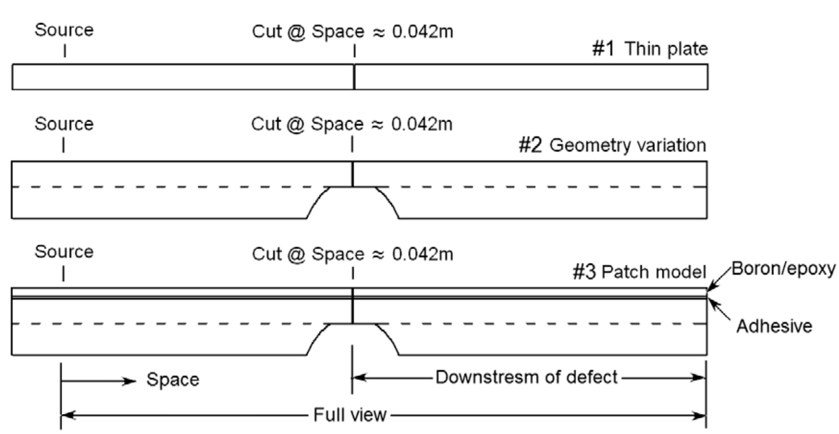


**Fig. 1.** Schematic of three models used for finite element analysis.