Engineering Failure Analysis 94 (2018) 182–194

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

A multivariate model to assess the probability of detection and sizing of defects in aluminum panels using eddy current inspections

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ABSTRACT

Typical inspection capability models are two-parameter models that estimate the probability of detection of certain size defects, flaws or cracks under controlled inspection conditions. This paper expands traditional detection models, including customary probability of detection and sizing models, to a multivariate model that includes additional factors that affect inspection outcome. To better assess inspection system capabilities, two procedures are examined. The first procedure involves the traditional model of detection and sizing based on a set of inspection system data which includes hit-or-miss data, sizing parameters, and various conditions pertaining to the inspection process. The second procedure implements a multivariate model of the flaw detection and sizing. The probability of detection, sizing, and certain shaping factors based on various inspection factors and conditions are introduced and modeled to demonstrate the impact of inspection system capabilities and conditions in the field.

1. Introduction

Damage growth in structures can lead to catastrophic failure of components and structures. Fortunately, in most cases damage can be detected before it propagates to a structural failure. One approach to damage detection is the utilization of incipient failure detection through non-destructive testing (NDT) techniques. NDT is used to search for defects in structural materials and components and to assess whether the material or component is safe or fit for its intended use [9]. There are several types of NDT techniques, each having its own process, equipment, personnel, and factors that are a part of an overall inspection system (IS). To assess the capabilities of an IS, probability of detection (POD) studies are executed utilizing a specific IS, in which procedure/technique, process, environment, structure, and other test variables are studied. However, the POD information obtained from a representative trial is applicable only to the exact conditions and defect types for which the POD trial inspections are performed [9]. This creates a two-part detection model (i.e., damage size and POD).

A case can be made for expanding the traditional approaches to a multi-parameter model [20]. Such an example exists in a Bayesian analysis approach applied to a joint-model that combines the POD model with a damage propagation model [19]. This methodology makes use of multivariate Gaussian process regression [17], which allows for the inclusion of external variables that affect damage detection and sizing, as represented by a set of multiple shaping factors that are correlated to the damage size. The approach in this paper can be incorporated into an analytical model that displays the relationship between external variables and their effect on conditions of the field inspection and inspector capabilities. For example, the methodology proposed by Schubert-Kabban et al., in which dependent data are incorporated into the current POD analysis standards [18], could be made more effective by incorporating the additional variables and the approach employed in this paper.

In this paper, two different approaches will be discussed that compare the effects of different input factors on the modeling of flaw detection. The first approach accounts for the effectiveness of the traditional POD and direct flaw sizing models including the model

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https://doi.org/10.1016/j.engfailanal.2018.07.028
Received 4 January 2018; Received in revised form 8 May 2018; Accepted 23 July 2018
Available online 25 July 2018

error, and the second approach accounts for the effect of multiple external variables or flaw shaping factors (FSFs) in addition to the direct flaw sizing and detection models. The motivation of this paper overall is to present both of these approaches and determine what effects certain FSFs have on the detection estimates for a series of flaw sizes.

2. Data acquisition and interpretation processes

To better understand the impact of external variables on POD, inspection data from tests under varying inspection conditions were generated through experimentation in a relevant field test environment. For this purpose, a total of 25 NDT inspections were executed with the following variations: (1) nine separate test panels exhibiting defects of different sizes, shapes, and quantities, (2) eight different inspection area configurations, and (3) six different inspectors.

2.1. Testing parameters

All NDT inspections were executed on a retired multi-mission helicopter series 60 “Romeo/Sierra” airframe (MH60 R/S) [12]. A series of test panels was attached to the airframe. These nine test panels were made of Aluminum 7075 and measured 304.8-by-304.8 mm with a thickness of 3.18 mm.[1] A conceptual diagram of the test panel is depicted in Fig. 1. The top surfaces of the test panels were pretreated with a chromate conversion coating, a primer and a topcoat under the Type I specifications laid out by the MIL-C-5541 documentation [15]. The total coating system had an approximate thickness of 0.0762 mm. This was incorporated to mimic Naval aircraft structures and to mask any perturbation on the surface. A 254 square-mm inspection area was also marked for each test panel. The opposite sides of the test panels were imbedded with defects which were sought by the inspectors using eddy current equipment [2]. Defects were fabricated in these panels at a depth of 0.254 mm from the inspection surface to ensure that damage could be detected only by using a subsurface detection method (such as eddy current testing) [5]. Damage types prepared in each panel varied from flat bottomed holes as small as 0.762 mm to length-wise mandrel cuts as long as 127mm. The backside of the test panel is illustrated in Fig. 1, which has both a mandrel cut outlined (Example Defect #1) and a flat-bottomed hole (Example Defect #2). The test panels contained up to ten defects on the uncoated side that were either drilled flat bottomed holes or slots cut with a mandrel. The test panels were affixed to the airframe with the defect side facing down so that the inspectors had to detect the small flaws in each panel using the detection equipment.

The eight inspection areas were varied in their degrees of physical and visual hindrances to the tester. For example, in one inspection area the inspector was able to see the surface under detection analysis, while in another inspection area the inspector was unable to see it. A relative assessment of each inspection location was performed using the Ovako working posture assessment system to help determine the relative difficulty of inspection in the chosen area [11].

Six inspectors of various capabilities and experiences [2] performed the tests. Their professional backgrounds ranged from a few years of NDT experience to highly skilled inspectors with more than twenty years of experience. Four of the inspectors were certified Eddy Current Level III inspectors by the American Society for Nondestructive Testing for electromagnetic testing techniques [21].

2.2. Test process

The inspection system (IS) testing procedure was designed to acquire sets of data based on a variety of testing conditions. All affixed test panels were inspected by the inspectors in a simulated field inspection condition. The inspectors utilized a Nortec 2000+ EMI eddy current instrument [16], and a choice of three pencil probes to perform the inspection. The probes used for freehand surface scanning were provided by EC/NDT [7] and possessed a drop at an angle of 0, 45, and 90 degrees [2]. Eddy current inspection utilizes electromagnetic induction to detect flaws in conductive materials. The inspector calibrates the instrument and then inspects the test panel according to a documented procedure [2]. When the inspector detected a defect, the position of the damage was marked and the instrument's amplitude response and the position and size of the detected damage was recorded.

A test monitor timed the duration of tests and measured the temperature of the environment. After the test, the inspector filled out a survey based on the NASA Task Load Index (TLX) [10], to provide a self-assessment on different testing conditions encountered during the test. This process was repeated for each test. With multiple tests under varied conditions, several external variables, or FSFs, can be correlated to the inspectors' performances. The following external variables were evaluated for each inspector and each test [2]:

- Accessibility and restrictions of inspection area
- Comfort level and degree of fatigue of inspection body position
- Visibility of inspection surface through blockage and/or angle of surface to inspector's sight
- Reported damage (flaw) size and quantification
- Quantity and type of simulated damages in the test panels
- Inspector's background, prior training, education, and experience

The inspection position, test panel, and inspector's background were all rated on an ordinal scale from 1 to 5, with 5 indicating the

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[1] The original design of these NDT inspections were in English units and are converted to the SI units in this paper.