Military Aircraft Structures Airworthiness Advisory Group

Paper 122

Development of a protocol for acceptance of new NDT capability in the air domain.

Professor Robert A Smith

Department of Mechanical Engineering, University of Bristol, BS8 1TR

9 October 2014

DISTRIBUTION

Task Sponsor

Dr Steve Reed, Dstl

MASAAG Members

Mr Mike Overd, AgustaWestland
Mr Kevin Fisher, BAE Systems
Mr Mark Palmer, Marshall Aerospace
Mrs Alison Mew, QinetiQ
Wg Cdr Matt Brennan, MAA
Lt Cdr Darren Jones, MAA
Sqn Ldr Richard Ponting, MAA
Sqn Ldr James Phillips, DE&S
Mrs Mandy Cox, MAA
Mr Tom Bell, MAA
Dr Richard Raistrick, MOD
Mr Tom Cook, Airbus UK
Mr David Patterson, Bombardier Aerospace

Authorship Panel

Prof Paul Wilcox, University of Bristol.
Dr Luke Nelson, University of Bristol.
Dr Steve Reed, DSTL
Mr David Hallam, DSTL
Mr Alex Ballisat, University of Bristol
Dr Richard Raistrick, MOD
Mr Tom Cook, Airbus UK
Mr David Patterson, Bombardier Aerospace
Mr Steve Dosman, Marshall Aerospace
Mr Tony Whitelaw, MAA
Mr Brian Morgan, MOD

International

Dr Geoffrey Hugo, DSTO, Melbourne, Australia and TTCP TP-5.
Prof Tony Dunhill, Rolls Royce plc, and NATO panel on NDT.

Paper Closure Statement

A draft version of MASAAG Paper 122 was circulated to all MASAAG members for comment on 24 July 2014. Eight comments were received and incorporated into the paper. The paper was ratified by the 77th MASAAG and it was agreed to take forward the route for introducing, demonstrating and reviewing a protocol for model assisted technique validation on new NDT capabilities.

EXECUTIVE SUMMARY

In 2011, the Military Aircraft Structures Airworthiness Advisory Group (MASAAG) recognised considerable difficulties experienced in introducing new non-destructive testing (NDT) capability into the military air domain over the preceding 15 years. MASAAG Paper 119 was then commissioned to identify the reasons underlying these difficulties and it was published in 2012. One of the main barriers identified was the lack of a proven historical track record on which to base an assessment of the reliability of a new capability. The recognised practice for validating *conventional* NDT techniques was to rely on experience, inspection evidence and engineering judgement in deciding what size of defect would be reliably detectable. The accepted route for validation of new techniques – a full *probability of detection* (POD) trial - was generally considered too costly in time and effort. Paper 119 proposed a mechanism for the introduction of new NDT capability based on model-assisted reliability assessment, removing the need for lengthy and costly POD trials. The objective for the future programme of work is to draft, demonstrate, review and introduce a protocol for technique validation along these lines.

Four parts are proposed to the required programme: 1) underpinning research and modelling for new NDT technologies, 2) drafting of the proposed protocol, 3) demonstration of the approach on one conventional and one new technology, 4) extension to inspection of composites. In order to make effective progress in each of these areas, a coordinated multi-party approach is required. This will include: an engineering doctoral (EngD) student through the UK Research Centre for NDE (RCNDE); pro-active involvement in the BINDT Aerospace Group, which has an objective to generate such a protocol; a funded programme of work lasting three to four years - competitively tendered; and the MASAAG NDT Working Group. The whole programme will be under the review and endorsement of the MASAAG membership, monitored by DSTL, with technical oversight provided by aerospace NDT experts at the University of Bristol.

The short- and long-term needs for new NDT technologies in the military air domain, as well as the fields of expertise of those already engaged in this programme, make ultrasound the obvious choice of NDT modality for demonstrating the new protocol. Phased-array ultrasound has been identified as the new technology that will offer the most benefit to MOD. The chosen application for part 3) - staged trials of the protocol - is the detection of cracks from fastener holes using angle-probe ultrasonic inspection, from manual swivel-scanning with operator-based analysis to automated phased-array scanning with automated analysis. The modelling EngD has already commenced through the UK RCNDE with experts in phased-array ultrasound at the University of Bristol. Phased-array can lead to smaller detectable defect sizes, increased reliability and reduced false calls. Ultimately this will result in wider inspection intervals, extensions to service life, and future aircraft will be lighter and have enhanced performance.

AUTHORSHIP

Principal Authors:

Prof Robert A Smith, University of Bristol

Authorship Panel (if used):

Prof Paul Wilcox, University of Bristol
Dr Luke Nelson, University of Bristol
Dr Steve Reed, DSTL
Mr David Hallam, DSTL
Mr Alex Ballisat, University of Bristol

TABLE OF CONTENTS

ABBREVIATIONS

AANC	Airworthiness Assurance NDI Validation Centre
AFRL	Air Force Research Laboratory [USA]
BVID	Barely visible impact damage [in composites]
CVID	Clearly visible impact damage [in composites]
CAA	Civil Aviation Authority
DSTO	Defence Science and Technology Organisation [Australia]
EASA	European Aviation Safety Agency
EDM	Electrical discharge machining (also known as spark-erosion)
FAA	Federal Aviation Administration
MAA	Military Airworthiness Authority
MAPOD	Model-assisted probability of detection
MASAAG	Military Aircraft Structures Airworthiness Advisory Group
MED	Multiple-element damage
MOD	Ministry of Defence
MSD	Multi-site damage
NANDTB	National Aerospace NDT Board
NDE	Non-destructive evaluation
NDI	Non-destructive inspection
NDT	Non-destructive testing
NTIAC	Non-destructive Testing Information Analysis Centre
OSD	Out of service date
PFP	Probability of false positive indications
POD	Probability of detection
RAAF	Royal Australian Air Force
RAF	Royal Air Force
RCNDE	Research Centre For NDE (UK)
RN	Royal Navy
SHM	Structural health monitoring
SI	Structural integrity
TTCP	The Technology Cooperation Programme
USAF	United States Air Force
WFD	Widespread fatigue damage

1 INTRODUCTION

1.1 BACKGROUND

1.1.1 MOTIVATION

In 2011, the Military Aircraft Structures Airworthiness Advisory Group (MASAAG) recognised considerable difficulties experienced in introducing new non-destructive Testing (NDT) capability into the military air domain over the preceding 15 years. MASAAG Paper 119 [1] was then commissioned to explain the reasons underlying these difficulties and this was published in 2012. The conclusions of Paper 119 will be presented in this section but its content will not be otherwise reproduced in this paper.

The barriers to introduction of new NDT technologies that were identified by Paper 119 were as follows.

1. Reliance on personnel certification prevents introduction of NDT where no training or qualifications exist.
2. Lack of accepted minimum detectable defect size requires long and costly POD trials.
3. Inability of design authority to specify a required detectable defect size results in additional time and cost to determine full POD as a function of defect size.
4. Lack of training in conducting POD trials results in an inability to perform these in-house.
5. Poor understanding of the read-across between artificial and real defects and structures results in an over-optimistic assessment of defect detectability.
6. NDT for composite structures requires a different treatment, and informs a different approach to structural integrity.
7. Inspection of large areas means defect location can be more important than defect size and there is no mechanism for dealing with this.
8. Automated analysis and decision-making methods need special consideration when determining defect detectability. This is not understood and may prevent their use.

Barriers 1 to 5 can be summarised as the need for a new strategy for validation of techniques using novel technologies where there is no proven historical track record on which to base an assessment of NDT reliability. In fact, barriers 6 to 8 also fall into the category of a shortfall in technique validation capability, but they address more specific inadequacies for composite materials, large-area inspections (including structural health monitoring) and automated analysis and decision-making methods.

1.1.2 NDT TECHNIQUE VALIDATION

The recognised practice for validating *conventional* NDT techniques and work instructions (EN4179 definitions) is currently to rely on experience, inspection evidence and engineering judgement in deciding what size of defect would be reliably detectable. However, for validation of new techniques, the accepted route – a full *probability of detection* (POD) trial – is often considered far too costly and resources for such trials are generally unavailable.

Paper 119 recognised considerable potential for reducing the time and cost of certifying new technologies and a three-pronged approach was suggested. Firstly, if a required defect detectability has been specified, this minimises the size of the POD trial and would also allow some optimisation of the decision threshold to minimise false calls. Secondly, if the technique is required to achieve the smallest possible detectable defect size then, whilst a full POD trial is needed, there are potential reductions in the size and cost of the POD trial if the distribution of defect sizes is optimised carefully to minimise the total number of defects required. Thirdly, by targeted use of model-assisted POD (MAPOD), particularly the transfer-function approach, the cost of certification could be reduced significantly.

1.2 OBJECTIVE

Since the publication of Paper 119, the MASAAG has agreed to a programme to develop its proposed mechanism for the introduction of new NDT capability based on model-assisted reliability assessment, removing the need for lengthy and costly POD trials. Hence, the objective for the future programme of work is to draft, demonstrate, review and introduce a protocol for model-assisted technique validation on new NDT capabilities.

Four parts are proposed for the work programme:

1) underpinning research and modelling for new NDT technologies,

2) drafting of the proposed protocol,

3) demonstration of the approach on one conventional and one new technology,

4) extension to inspection of composites.

In order to make effective progress in each of these areas, a coordinated multi-party approach is required. This will include: an engineering doctoral (EngD) student through the UK Research Centre for NDE (RCNDE); pro-active involvement in the BINDT Aerospace Group, which has an objective to generate such a protocol; a funded programme of work lasting three to four years -

competitively tendered; and the MASAAG NDT Working Group. The whole programme will be under the review and endorsement of the MASAAG membership, monitored by DSTL, with technical oversight provided by aerospace NDT experts at the University of Bristol.

1.3 SCOPE

This paper only addresses the development, testing and demonstration of a protocol for model-assisted reliability assessment in general. Composites, large-area and SHM methods, and automated analysis methods will be considered in the context of this protocol and its applicability to these situations.

Three other potential causes of difficulties in NDT development were identified in MASAAG Paper 119 [1] but these will not be addressed further in the current document, other than to list them here:

- personnel certification when no training material, courses or qualifications exist;
- poor understanding of structural integrity (SI) by NDT specialists and vice versa, leading to inappropriate and unhelpful specification of NDT requirements;
- resourcing and deployment issues amongst military personnel.

However, it is hoped that the proposed programme will go some way to building structural-integrity reasoning into the technique-validation protocol, thus addressing the second of the above points.

Note that this document uses the EN4179 definition for ‘technique’, which means a “category within a method”, and for ‘work instruction’, which means a “document detailing the NDT technique and testing parameters to be used for the inspection of a specific component, group of parts (e.g. “aluminium extrusions” or “steel brackets”), or assembly”.

1.4 STRUCTURE

Section Two of this paper provides an introduction to model-assisted reliability assessment, including references to existing documents. Section Three considers the development of a protocol, other programmes engaging with this problem and a potential route for standardisation of the approach and approval of the protocol. Sections Four to Six are more specific about the programme of work that will be put out to competitive tender in 2014, including a description of the chosen demonstration techniques (Section Four), outstanding requirements for modelling (Section Five), and potential collaborators or participants in the programme (Section Six).

2 MODEL-ASSISTED RELIABILITY

2.1 EXISTING STANDARDS AND GUIDANCE

The high cost and long duration of experimental POD trials for NDT technique qualification has made them impractical and has led to the search for an alternative approach. Model-assisted POD (MAPOD) offers potential cost benefit by replacing certain aspects of the POD trials with theoretical models. It is envisaged that each contributor to NDT reliability of a work instruction could be modelled separately and the contributions combined to determine the overall POD.

MAPOD studies divide broadly into two categories: 1) full modelled approach and 2) transfer-function approach. In the full modelled approach, the actual physics of the NDT inspection is modelled, including how it is affected by the various adjustable parameters. The transfer-function approach is less ambitious and combines laboratory-based experimental trials on artificial defects in artificial specimens, which are much quicker and less costly to perform, with modelling of the difference in defect detectability of real defects in real structure and a realistic environment compared with the artificial trials.

In Paper 119 [1], Appendix D attempts to summarise the benefits and current status of POD modelling, with an initial literature review. Paper 119 Appendix B also contains a paragraph summarising the MAPOD section of MIL_HDBK-1823A [2]. A recent TTCP assignment [3] reported the benefits from several MAPOD studies carried out in Australia, Canada, USA and UK.

Appendix E in Paper 119 [1] summarised an example of MAPOD using the transfer-function approach developed by DSTO in Australia for a crack inspection scenario [4-11]. The transfer functions were developed and experimentally verified to read across from artificial to real cracks and artificial to real structure.

QinetiQ Ltd developed a similar method for crack detection in Tornado spar flanges [12-14] for the MoD. But in this case the fastener holes were cold-worked, creating a significant difference between the sensitivity to artificial defects (EDM notches) and real cracks, which might be tightly closed due to residual stresses. The transfer function approach involved modelling the residual-stress field around a cold-worked hole in order to determine how closed the crack would be for different external loads on the wing at the time of inspection. It was found that loading the wing significantly improved the crack detectability.

2.2 MODEL-ASSISTED CERTIFICATION

The model-based certification process will require models for each stage in the inspection process. These models should take as inputs the inspection parameters specified by the procedure and location-dependent structural information for all locations being considered. Each model will address an element of the inspection, such as ultrasound propagation and interaction with a defect, or the generation of an acoustic emission by a crack growth event and subsequent propagation to a sensor. The output of each model will be the contribution from that element of the inspection to the probability of detection and likelihood of false calls over a range of defect sizes, see Figure 1.

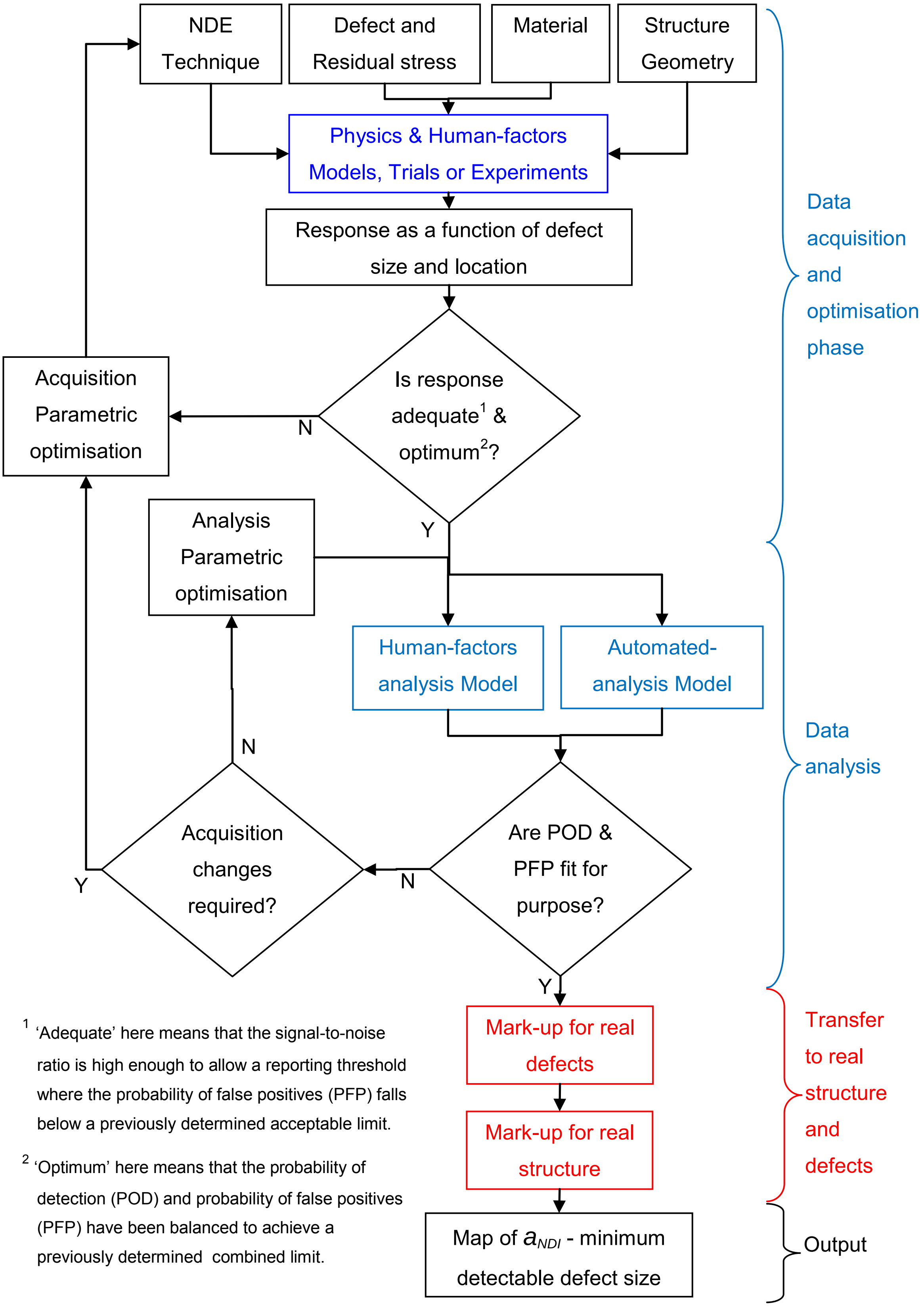
The complexity of the ‘Physics Model’ element (blue in Figure 1) of a model-based reliability model varies enormously depending on the NDT method and the structure concerned. For example, normal-incidence ultrasonic propagation and interaction with defects in isotropic metals is relatively simple but oblique-incidence ultrasound in anisotropic materials such as composites or single-crystal alloys is highly complex.

There is scope, in the absence of a full model for an inspection method, to base the model on experimental measurements of defect responses in simulated structure with a range of well-controlled and known defect sizes. This is known as the ‘transfer-function approach’ to model-based POD, where it is necessary to understand how the transfer to real structure and real defects will influence the defect detectabilities and false-call rates.

Figure 1 also demonstrates how such models can be used to optimise the inspection itself. Inspection parameters can be varied through a range of possible values in order to find the optimum set of parameters to maximise the response to defects and minimise false calls. This process is known as ‘multi-dimensional optimisation’.

2.3 FORMALISING THE MAPOD APPROACH

A MAPOD example developed by QinetiQ for Tornado was successful in reducing certification costs considerably, but there was no formal mechanism to sign off the work instruction because of a lack of an agreed certification protocol. MIL_HDBK-1823A [2] contains a protocol for using MAPOD and this should be considered for formalising the use of a MAPOD approach to certification of novel NDT methods.



[1] 'Adequate' here means that the signal-to-noise ratio is high enough to allow a reporting threshold where the probability of false positives (PFP) falls below a previously determined acceptable limit.

[2] 'Optimum' here means that the probability of detection (POD) and probability of false positives (PFP) have been balanced to achieve a previously determined combined limit.

Figure 1- *Proposed protocol for a model-based reliability study for a new NDT capability. This incorporates both the fully modelled approach (blue) and the transfer-function approach (red), which will have a different emphasis in each scenario.*

2.4 WORKED EXAMPLE

A good example of the MAPOD approach in its ‘Transfer Function’ mode was documented by DSTO for crack detection from fastener holes in their F111 wing skins [4-11]. A similar approach was used by QinetiQ but for second-layer (spar-flange) cracks emanating from cold-worked holes [12-14].

- **Response as a function of defect size and location.** This was not a ‘fully modelled’ approach because the initial ‘Physics Model’ in the flow diagram of Figure 1 was replaced with trial data from EDM-notch ‘defects’ in simulated structure, gathered using an automated scanner and a recirculating couplant system, as detailed in the actual inspection on the F111 wings. Different locations of defects up the shank of the fastener hole were studied.
- **Human Factors.** The Human Factors were studied by DSTO using human operators to analyse the data obtained in the above trials. POD studies were performed on EDM notches in simulated wing-skin structure to determine the performance of manual analysis methods according to a detailed procedure.
- **Mark-up for real defects.** The interaction of the ultrasound from single-element probes with EDM notches, and cracks, in simulated specimens were studied experimentally, and modelled in the case of QinetiQ’s cold-worked holes. The difference between the responses indicated a transfer function from EDM notches to real cracks, and a resulting ‘mark-up for real defects’ in *minimum reliably detectable defect size,* a_{NDI}. The ultimate goal of a validation exercise is to establish the value of a_{NDI}. The main issue here for DSTO’s F111 application was that real cracks propagating under fighter-aircraft loading spectra, with occasional very high loads, have a residual compressive stress zone around the crack tip. This zone tends to close the crack, making that part invisible to ultrasound. QinetiQ found that the residual compressive hoop stresses around a cold-worked fastener hole also forced cracks to be closed near the hole. They showed that the application of an external load could overcome both the cold-worked stress and the crack-tip residual stress mentioned above, re-opening the crack and making it visible to ultrasound [14]. But it may not have been practicable to apply such a stress during the inspection. These studies concluded that a mark-up in a_{NDI} could be applied but that this varies with externally applied local stress at inspection time.
- **Mark-up for real structure.** Data was acquired on real wings, fatigue-test wings and on simulated structure to determine any mark-up due to the structure itself. This can be location dependent. For example, if an external load is applied in order to open cracks, that load will not produce the same local stress at each fastener. Other effects include

the level of bonding to the second layer or sub-structure and the interference fit of the fasteners in the holes, which often is highly variable in an older aircraft. These effects may not be crack-size dependent but can still affect the probability of detection and the false-call rate.

The process for combining the outcomes of the above contributions to reliability was by using a mark-up in the *minimum reliably detectable defect size* from the real crack transfer model.

3 PROTOCOL DEVELOPMENT

3.1 EXISTING PROTOCOLS

At the start of the funded programme there will need to be a study to discover the full extent of existing standards and protocols. A useful article covering the inspection qualification process for the nuclear industry was published in 2009 [15].

The author is aware of the following relevant documents:

- BSI document PD CEN/TR 14748:2004 [16]. A general document about how to qualify a non-destructive test.
- ENIQ Report No 31 [16]. A ‘consensus document’ created originally in 1995, but updated twice since then, by the European Network for Inspection and Qualification. Whilst not restricted in its applicability, it was developed by and for the nuclear industry.
- MIL-HDBK-1823A [2]. USAF document, which is the main guidance for determining the reliability and minimum detectable defect size for novel techniques. It covers the main methods for determining POD. This is summarised in Appendix B. In MIL-HDBK-1823A, NDT systems are classified into one of three categories:-
    - Systems which produce only qualitative information on the presence of flaws, known as hit/miss data, e.g. penetrant testing, magnetic particle testing.
    - Systems which provide a signal which is a quantitative measure of the flaw, â, to a flaw of size, a, known as “â vs. a” data, e.g. eddy-current testing, ultrasonic testing.
    - Systems which produce an image of the target inspection area and its surroundings. Data from these systems can be further analysed to produce either hit/miss or â vs. a data.

3.2 INTERESTED BODIES

The British Institute of NDT (BINDT), within its Aerospace Group, has also identified the need for a best-practice guide for technique validation, which includes model-assisted approaches. A Technique Validation Working Group has been established to begin the process of developing this guide, led by Dr Tim Barden of Rolls Royce, covering NDT, and Prof Peter Foote of Cranfield University, covering SHM. It is intended that several workshops will be organised during the development of the guide to ensure it is fit for purpose. This initiative will fit well with the MoD programme proposed in this paper and it will be a requirement of the winning bid that they collaborate with BINDT's Aerospace Group on developing the best-practice guide and the proposed protocol for MoD use. Other potentially interested parties include:

- European Network for Inspection and Qualification (ENIQ)
- Commercial Aircraft Composite Repair Committee (CACRC)
- SAE International
- ADS Group (Aerospace Defence and Security)
- British Standards Institute (BSI)
- Defence Science and Technology Organisation (DSTO), Australia
- Anglo-Australian Memorandum of Understanding for Science and Technology (AAMOUST)
- The Technology Cooperation Panel (TTCP)
- Air Force Research Laboratory (AFRL), Dayton, Ohio, USA
- Naval Air Systems Command (NAVAIR), Patuxent River, Maryland, USA.
- NRC, RMA – Canada
- NRL – The Netherlands
- NATO STO AVT Panel - NDT Working Group
- National Physical Laboratory (NPL), Teddington, UK.

3.3 ROUTE FOR DRAFTING, REVIEW AND APPROVAL

The protocol will be drafted by the contractor on the MoD programme and will be overseen by the BINDT Aerospace Group and its Technique Validation Working Group. Trials planned in this paper will contribute to the review and re-drafting of the protocol.

The optimum route for reviewing and issuing the protocol document has yet to be established, but MoD would like it to be adopted in the civil sector too, and preferably internationally. Possible routes are through organisations such as BSI, ISO, IEC, ENIQ, etc. If the protocol is elevated to a suitable 'standard', it will be possible for future Def Stan updates to reference it.

It is anticipated that contractor attendance will be required at four BINDT Aerospace Group meetings and four Technique Validation Working Group meetings per year, for the duration of the project. In addition, the contractor will attend meetings of the chosen standards organisations and respond to correspondence.

4 PROTOCOL DEMONSTRATORS

4.1 OBJECTIVES

The main objective of the demonstrator programme is to prove the effectiveness of the model-assisted reliability protocol for technique validation. As part of that process, it is anticipated that the protocol itself will undergo several stages of refinement, as a result of the experience of applying it to real inspection requirements. It has been agreed that this protocol refinement and trial needs to be performed initially on a conventional inspection where there is a good body of evidence from trials and experience with which to compare.

In order to prove the protocol's effectiveness for new NDT technologies, it is also necessary to perform a trial on the same defect-structure inspection scenario but with a new technology, preferably related to the conventional one already studied. There are a few inspection scenarios where not only new technologies, but also large-area issues, automated data acquisition and automated analysis have also been considered. Such a scenario offers opportunities for assessing the protocol's ability to deal with these aspects too.

Finally, a trial of an inspection of composite materials for detection of accidental impact damage will be required, assuming the above trials are performed on metallic structures.

4.2 TARGET DEFECT, STRUCTURE AND NDT METHOD

Given the fields of expertise of the people and organisations already engaged in this programme, as well as both the short- and long-term needs for new NDT technologies in the military air domain, the obvious choice of NDT modality for the whole programme is ultrasound. Phased-array ultrasound has been identified as the new technology that will offer the most benefit to MOD. A modelling EngD is already set up through the UK Research Centre for NDE (RCNDE) with world experts in phased-array ultrasound in the Ultrasonics and NDT Group at the University of Bristol. Phased-array can lead to reduced detectable defect sizes, increased reliability and reduced false calls. Ultimately this will result in wider inspection intervals, extensions to service life, and future aircraft will be lighter and have enhanced performance.

The target inspection proposed for the majority of the protocol demonstrations is the detection of cracks emanating from fastener holes in two-layer aluminium structure, using angle-probe ultrasound. This is an extremely common manual inspection as well as one that has been extended to automated single-element data acquisition [4-11], manual and automated phased-array acquisition, full-matrix capture array operation, and automated analysis and sentencing [12-14]. In addition, it has been the subject of model-assisted reliability studies in the UK, USA and Australia in the past, so a considerable amount of experience has been accumulated [4-14].

4.3 STAGED TRIALS

As discussed above, it is proposed that a series of staged trials would be best for illustrating the effectiveness of the protocol across its breadth of inspection scenarios. For this reason, the following stages have been defined.

1. Manual Angle-Probe Ultrasonic Technique
2. Array-Probe Manual Sector-Scan Inspection
3. Array-Probe Manual Lateral Scan Inspection
4. Full Matrix Capture
5. Automated Acquisition
6. Automated Analysis

These are described individually in sections 4.3.1 to 4.3.6.

4.3.1 MANUAL ANGLE-PROBE ULTRASONIC TECHNIQUE

A commonly prescribed inspection for military structures is a manual angle-probe ultrasonic ‘swivel’ scan. In this technique the operator points the beam from the transducer towards the potential crack location and detects reflections from corner reflectors, which send the ultrasound back in the reverse direction, to the transducer (see Figure 2). Signals are received not just from cracks, but also from the corner formed by the fastener hole and each in-plane interface between layers. The potential for numerous reflections, only some of which come from cracks, makes this a highly skilled inspection. It is called a swivel scan because the probe is scanned through a range of angles, which include the direction of the fastener and any potential cracks either side of it.

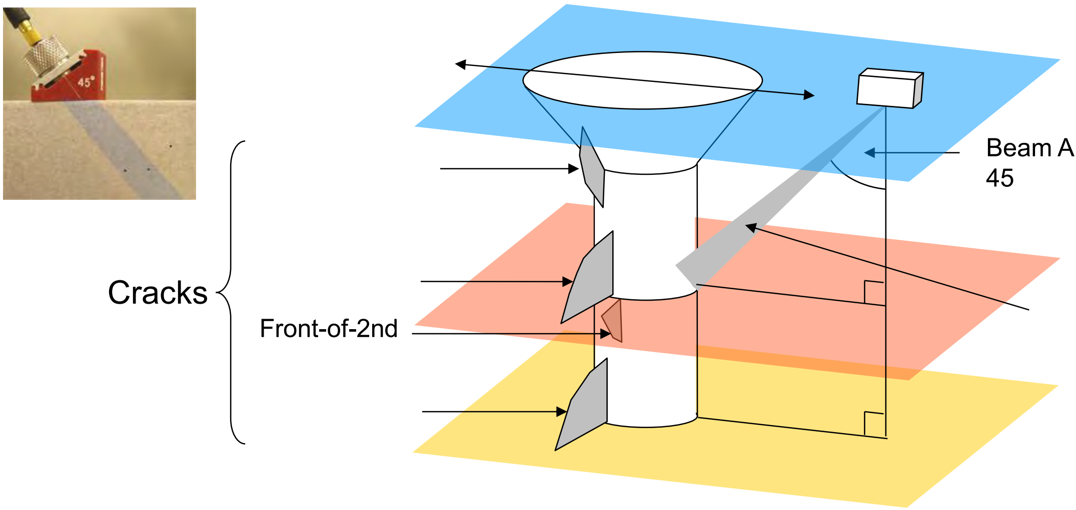


Figure 2. Diagram showing the angle-probe ultrasonic inspection for crack detection. Cracks in four potential locations are illustrated.

In most manual inspections, only the first layer is inspected because of the inconsistency of coupling into the second layer combined with the complexity of understanding the numerous different reflections coming from the second layer. This is the main reason for recent moves towards automated acquisition and separate analysis, enhanced with automated detection and sizing of indications.

4.3.2 ARRAY-PROBE MANUAL SECTOR-SCAN INSPECTION

It has been suggested that a manual inspection for cracks at fastener holes would be enhanced by using a phased-array system in sector scan mode with the probe mounted on an angled wedge and with the probe in line with the fastener, such that the sector is swept in a vertical plane (see Figure 3). This would inspect for a range of crack locations up the fastener shank.

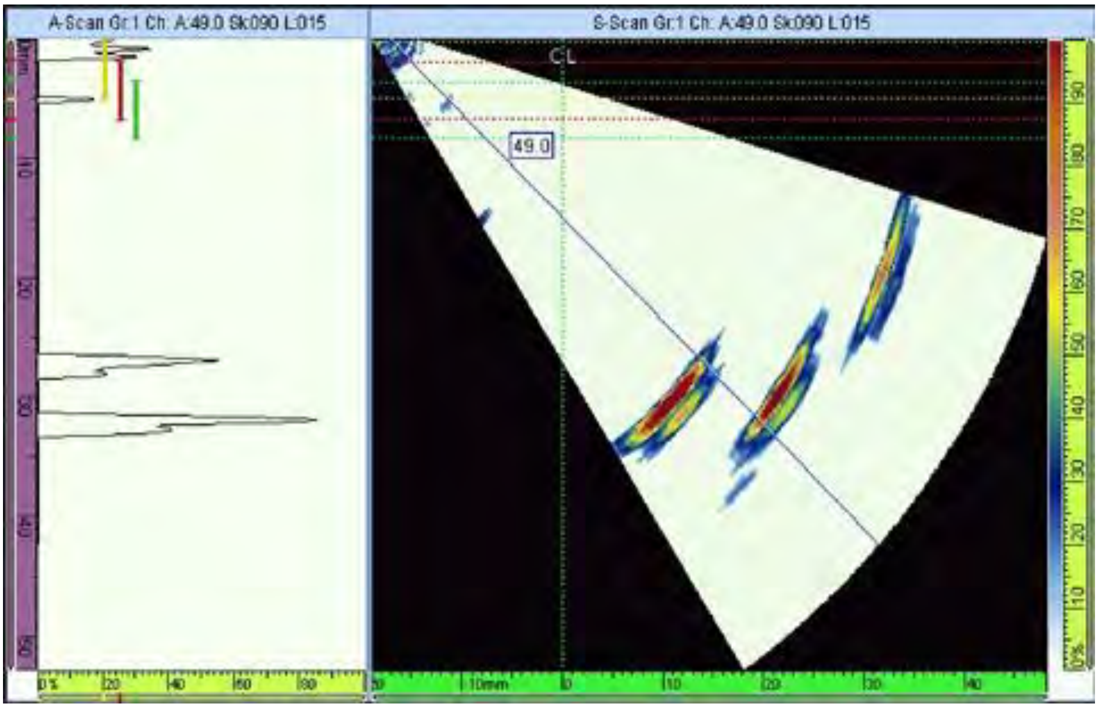


Figure 3. An example of a vertical-plane sector scan showing a slice through the structure. Courtesy of Olympus KeyMed Ltd.

4.3.3 ARRAY-PROBE MANUAL LATERAL SCAN INSPECTION

A more common configuration for crack detection at fastener holes is to hold the array parallel to the surface on a wedge (see Figure 4), allowing sweeping of the beam laterally, either as a linear scan or a sector scan. In this way numerous crack orientations can be detected and both sides of the fastener hole can be inspected in one pass. It is normal to inspect along a line of wing-spar fasteners with the ultrasound pointing inboard or outboard, as opposed to the fuselage inspection illustrated in Figure 5, but the basic principle is that the ultrasound beam should be perpendicular to the crack direction as shown in Figure 2.

Figure 4. Typical probe configuration for a lateral scan phased array inspection. Photo courtesy of Olympus KeyMed Ltd.

Figure 5. Probe orientation for fuselage inspection with crack direction fore-and-aft. Courtesy of Olympus KeyMed Ltd.

The resulting scan images are shown in Figure 6 for the Omniscan equipment and test specimen illustrated in Figure 4 and Figure 5 respectively. The 0.230” defect gives a weaker indication, probably because it is not aligned perpendicular to the ultrasound beam angle.

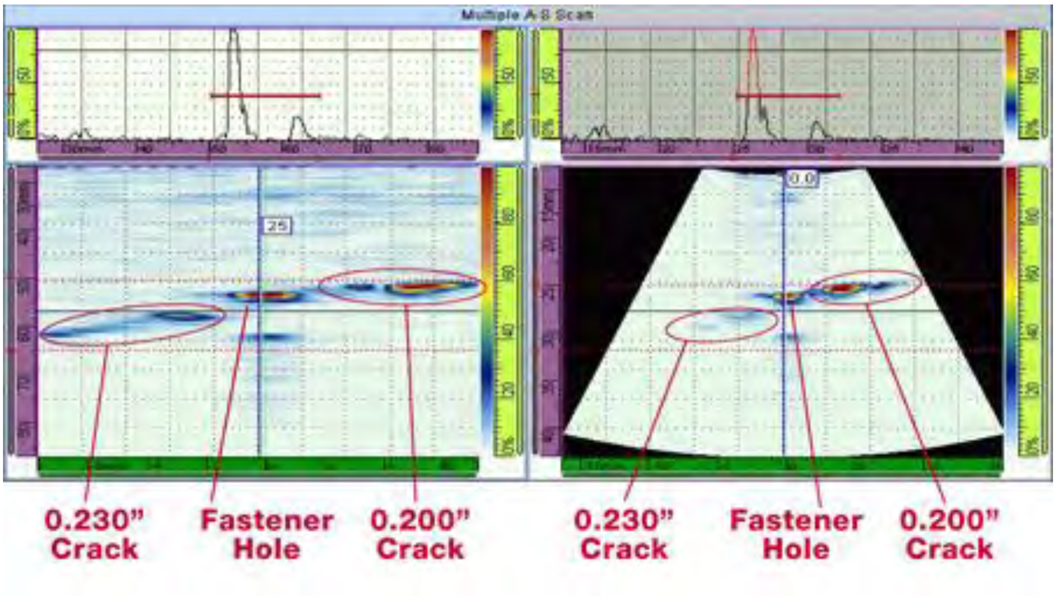


Figure 6. OmniScan print screen showing crack detection using first configuration. Lateral linear scan (left); lateral skewing scan (right). Courtesy of Olympus KeyMed Ltd.

Images shown in Figure 6 are slices in line with the ultrasound plane, at 45 degrees through the structure. Defects can also be imaged in both B-scan (out-of-plane) and C-scan (in-plane) slices and examples of these are Figure 7. In the B-scan, a crack defect appears

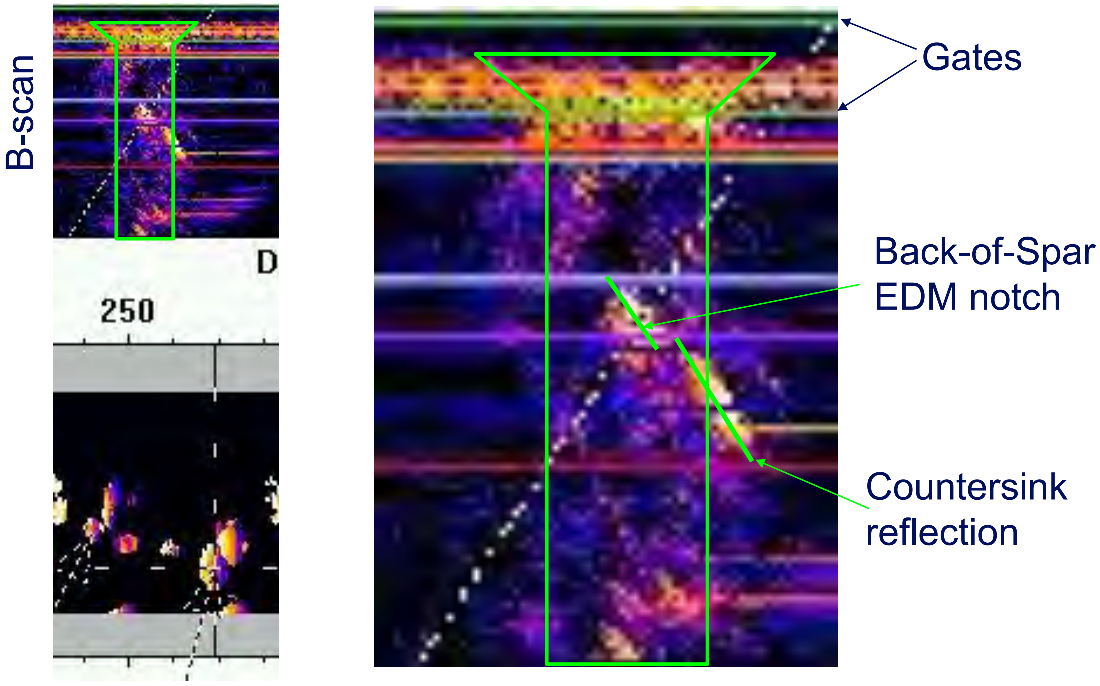


Figure 7. Example of reconstructed B-scan (top-left) and C-scan (bottom-left) images for a simulated (EDM notch) defect. Annotations on the B-scan on the right explain the different reflections. Image courtesy of QinetiQ Ltd.

4.3.4 FULL MATRIX CAPTURE

Probably the most significant enhancement to phased-array technologies in the last 10 years has been the development of Full Matrix Capture (FMC) with advanced reconstruction algorithms that can apply customised focusing as a post-processing operation. In the FMC method, each array element is pulsed separately and, for each firing, an echo signal is received and stored for each element. If the system can acquire simultaneously on each element as a separate channel, then the acquisition rate is similar to conventional pulse-echo usage.

The benefits of FMC are numerous. The primary benefit is in resolution for imaging of defects, because, in the Total Focusing Method (TFM) reconstruction algorithm, each point in the final image can be made the focal point of the algorithm – effectively a new focal law for every potential defect location. This improvement is illustrated in the C-scan images shown in Figure 8. Signal-to-noise ratio (SNR) is improved because the response from a single location is generated from several (n) separate transmit-receive waveforms and incoherent noise is averaged, increasing SNR by a factor of approximately $\sqrt{n}$. In addition, there is an improvement in dynamic range because each transmit-receive waveform is captured at a higher gain and then combined with other waveforms, reducing digitisation noise and giving the potential for more ‘bits’ in the digital response at each location.

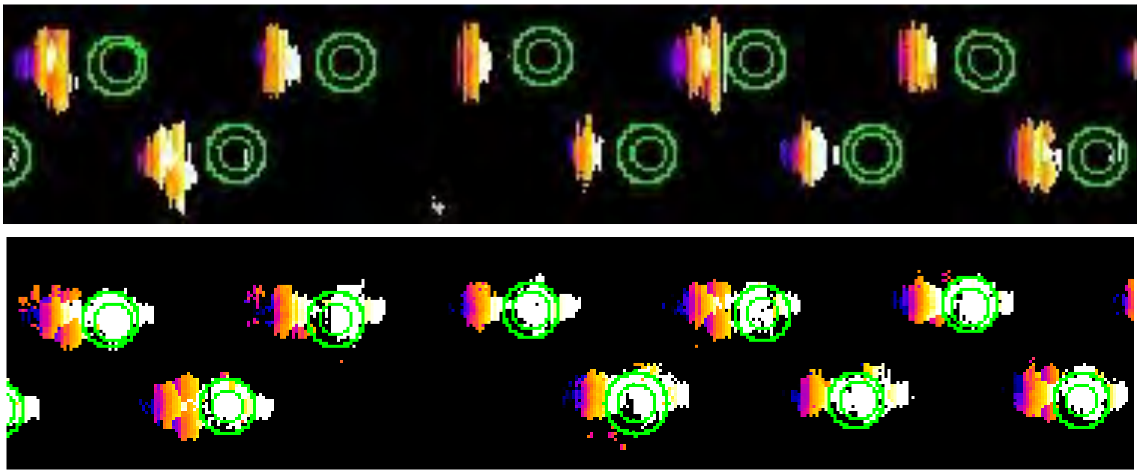


Figure 8. C-scan images from the interface depth showing a comparison of conventional single-depth focusing (top) and FMC with Total Focusing Method (bottom). The colour represents the time of flight of the reflection. Image courtesy of QinetiQ Ltd.

4.3.5 AUTOMATED ACQUISITION

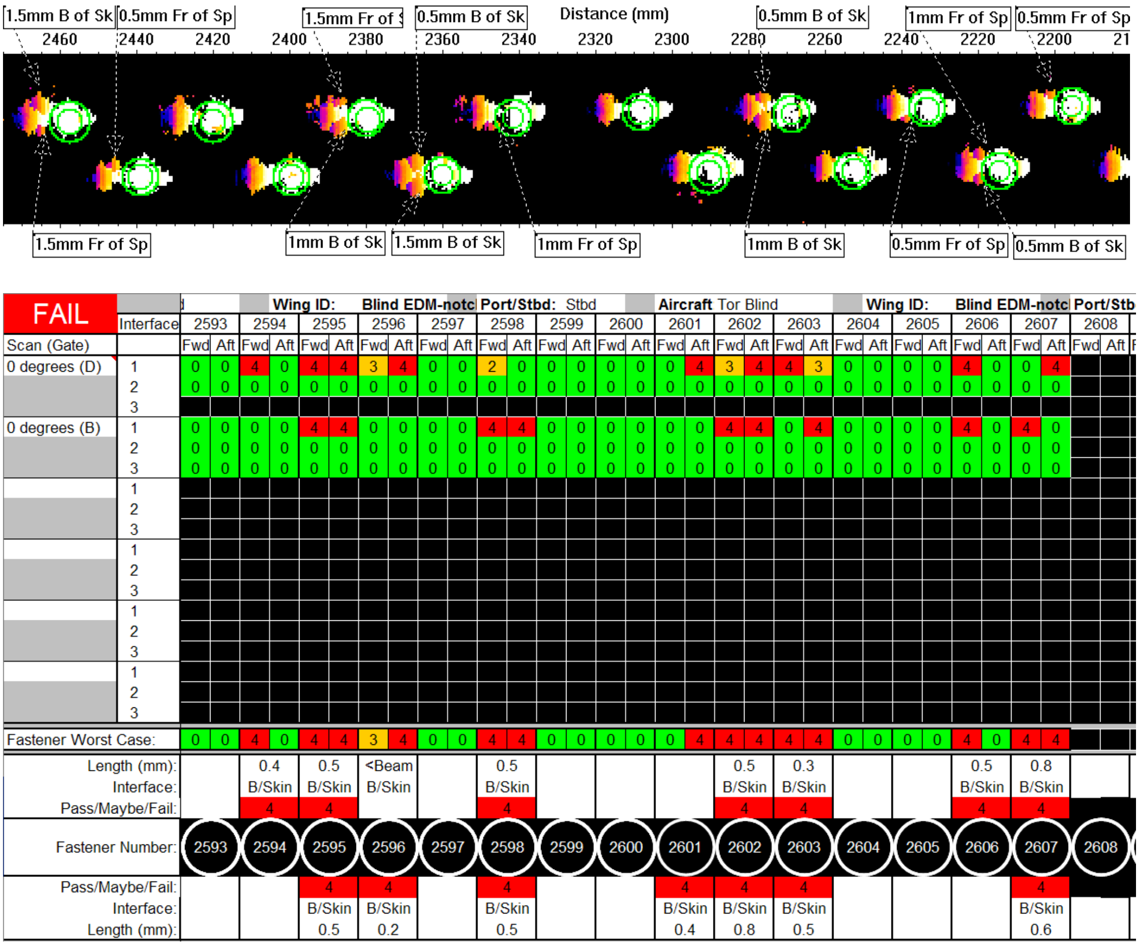
In order to obtain consistently high-quality images such as those in Figure 8, it is advisable to automate the acquisition. This has been done by DSTO with single-element probes scanned in a raster-scan [5] and by QinetiQ with a linear array [12-14]. There is an anticipated slight improvement in reliability due to scan consistency but otherwise the move to automated acquisition only affects the technique in that it is often with this development that acquisition and analysis are separated into two separate stages in the inspection, possibly performed by different people.

4.3.6 AUTOMATED ANALYSIS AND SENTENCING

Whilst automation of the data acquisition makes very little difference to the reliability of a technique, automating the analysis or sentencing completely changes the technique as well as the methods for determining reliability. An automated *analysis* method is defined here as one that does not in itself make decisions, but may automatically measure, compare measurements with thresholds and size indication. An automated *sentencing* method will decide whether an indication is reportable, recognise or classify defects and potentially determine either a confidence level or a severity category.

Fundamentally, an automated sentencing method is trying to reproduce the logic and reasoning used by a human decision-maker, but as a deterministic process that is not susceptible to changes in behaviour, tiredness, eyesight, intelligence or other human factors. By definition, this removes much of the statistical variability from the inspection, but also from any validation method. Given the same input data, an automated analysis and sentencing system will always output the same answers. This means that input data cannot be re-used and statistical approaches to validation have to be used with great care.

An example of an automated analysis and sentencing approach for crack detection at fastener holes was developed by QinetiQ and the output is illustrated in Figure 9. When a large number of fasteners have been scanned, the laborious task of manual analysis introduces potential errors due to fatigue and boredom, as well as a great amount of experience of never finding a defect. The QinetiQ system initially manipulated the 3D data set to correct for angle-probe distortions and reduce the footprint of the reflections. It then performed many measurements of the 3D location and size of each ‘indication’. It compared the measured locations with the stated range of possible defect locations relative to the fastener hole, resulting in three *location* criteria that could be met. A fourth criterion was based on the size of the indication. Then a traffic-light colour was used based on the number of criteria met (0-1: green, 2-3: amber, 4: red) and this indicated the confidence level that this was a true defect. Finally the size of the defect was estimated based on prior calibrations on the response from EDM notches – thus given an *equivalent EDM-notch length*. As two passes of each fastener were made, with the ultrasound beam in opposing directions, the results from these two scans were then combined into an overall estimate of confidence level and size. These results were displayed graphically.



d Wing ID: Blind EDM-notc Port/Stbd: Stbd Aircraft Tor Blind Wing ID: Blind EDM-notc Port/Stb

FAIL	Interface	2593		2594		2595		2596		2597		2598		2599		2600		2601		2602		2603		2604		2605		2606		2607		2608	
Scan (Gate)		Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft	Fwd	Aft
0 degrees (D)	1	0	0	4	0	4	4	3	4	0	0	2	0	0	0	0	0	0	4	3	4	4	3	0	0	0	0	4	0	0	4		
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	3																																
0 degrees (B)	1	0	0	0	0	4	4	0	0	0	0	4	4	0	0	0	0	0	0	4	4	0	4	0	0	0	0	4	0	4	0		
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	1																																
	2																																
	3																																
	1																																
	2																																
	3																																
	1																																
	2																																
	3																																
	1																																
	2																																
	3																																
Fastener Worst Case:		0	0	4	0	4	4	3	4	0	0	4	4	0	0	0	0	0	4	4	4	4	4	0	0	0	0	4	0	4	4		
Length (mm):				0.4		0.5		<Beam				0.5								0.5		0.3						0.5		0.8			
Interface:				B/Skin		B/Skin		B/Skin				B/Skin								B/Skin		B/Skin						B/Skin		B/Skin			
Pass/Maybe/Fail:				4		4						4								4		4						4		4			
Fastener Number:		2593		2594		2595		2596		2597		2598		2599		2600		2601		2602		2603		2604		2605		2606		2607		2608	
Pass/Maybe/Fail:						4		4				4						4		4		4								4			
Interface:						B/Skin		B/Skin				B/Skin						B/Skin		B/Skin		B/Skin								B/Skin			
Length (mm):						0.5		0.2				0.5						0.4		0.8		0.5								0.6			

Figure 9. Example (bottom) of the output from QinetiQ's automated analysis and sentencing system for cracks at fastener holes [13], applied to an EDM-notch test specimen. A traffic-light system is used to indicate confidence level, based on the number of 3D location and size criteria that are met, and the length of the defect is calculated from calibrated measurements on the C-scan (top). Finally, a Pass/Fail decision is made and displayed top-left. Courtesy of QinetiQ Ltd.

4.4 EXTENSION TO COMPOSITE MATERIALS

Due to the increasingly widespread use of composite materials in aircraft structures, it is a requirement to demonstrate the protocol on at least one inspection of composite structures. However, the above angle-probe ultrasonic crack-detection scenario is not faced with composite materials where the predominant in-service damage mechanism is in-plane delamination caused by accidental impact damage. As the standard inspection for this kind of damage is also large-area ultrasonic scanning, and often with phased-array probes, it should be possible to adapt the models, the scanner and ultrasonic NDT equipment to this application in order to extend the protocol demonstration to impact damage detection.

The real issues for validation of composite inspection are related to the link between inspection and structural integrity. This is for two reasons: firstly, structures are designed so that invisible (by eye) damage does not grow under fatigue, changing the role of repeat inspections; secondly, 'detection' of damage is often by visual methods and ultrasound is used subsequently to size the damage. Hence, the programme will also need to address these issues.

Finally, the future of accidental damage detection in composite structures will almost certainly include the use of structural health monitoring (SHM) using installed sensors. Whilst there are issues surrounding the business model and structural integrity for use of such systems, it is important to establish a route for validation and verification of these technologies prior to their large-scale introduction. Therefore, it is proposed that the issues of extension of the protocol to SHM should be considered as far as is practical, by collaboration with other organisations engaging in this field, such as Cranfield University, SAE, etc. The diagram in Figure 1 ends with a reference to a 'Map of a_{NDI} - minimum detectable defect size'. The reason for requiring a map, rather than just a single value, is that this anticipates a large-area inspection method or SHM, where the POD may depend as much on defect location as on defect size. This is an ideal scenario where a model-assisted approach could enable the location-dependence to be determined.

5 MODELLING RESEARCH REQUIREMENTS

5.1 ULTRASONIC PROPAGATION MODELS

5.1.1 CHOICE OF MODELLING SOFTWARE

For the proposed MAPOD demonstrator programme, the focus will be on ultrasonic inspection for cracks from fastener holes in aluminium structures, up to two or three layers thick, using both single and multi-element transducers. Models already exist, both in academia and commercially (eg CIVA) for such ultrasonic propagation, so this programme will assess those models, determine their capabilities and limitations, and use them as part of the optimisation and technique validation process outlined above. If shortcomings with those models are identified then it may be necessary to develop a bespoke model.

5.1.2 DEFECT AND RESIDUAL STRESS

The chosen defect type – out-of-plane cracks – are a major failure mechanism in metallic structures. They initiate in high tensile stress locations, often already degraded due to fatigue, and generally propagate at the highest-stressed point of the crack. This often means that cracks will grow across the corner between a fastener hole and a faying surface, forming a ‘corner crack’. However, they can also grow mid-bore and at the countersink-to-bore corner.

Oblique-incidence ultrasound directed at a corner crack can reflect off both the crack and the faying surface, resulting in a corner reflector, and sending the ultrasound back to the probe. Thus pulse-echo angle-probe inspection is commonly used to detect such cracks, the amplitude of the response being dependent on crack size, surface profile, crack angle and crack opening [4-10, 12-13].

When a crack grows under fatigue, the loading spectrum affects the residual stresses that form near the crack tip. If the loading spectrum contains occasional high stresses, such as in a fighter-aircraft spectrum, then a plastic zone forms at the crack tip and this exerts a compressive residual stress on the crack, tending to close it. Ultrasound is sensitive to crack opening and a closed crack will have a lower reflection coefficient, potentially making it invisible [5,14].

There are other causes of residual stresses that may close a crack, rendering it transparent to ultrasound, such as cold-working of the fastener hole and this effect will need to be modelled where it is relevant as a transfer function approach [14].

5.1.3 MATERIALS

The scenario chosen for most of the work involves homogenous metallic materials such as aluminium, but the model should also be capable of adaptation for composite materials, even though out-of-plane cracks are rarely the most important failure mechanism for a composite component. Matrix cracking may be detected using angle-beam ultrasound, but it is the subsequent delamination damage that is far more detectable and critical to the strength and performance of the structure. Thus, propagation in laminated structures should be included for the ultrasonic propagation model.

5.1.4 STRUCTURES

The geometry of the structure in relation to a defect location is an important element in determining the detectability of a defect. Ray-path models exist and are commonly used for checking that a defect is inspectable from a particular location, but these rarely include full diffraction effects and, therefore, cannot fully model the variation in response from different sized defects. A limited amount of allowance can be made for crack closure effects and different crack angles though.

5.2 HUMAN FACTORS MODELS

5.2.1 ACQUISITION STAGE

As well as modelling the Physics of the inspection, the scope for operator error, probe handling, access restrictions, etc, on the reliability of the inspection must be factored into the acquisition-stage modelling. It is expected that various classes of inspection will be established, which share similar human-factors issues, so that the number of these models can be manageable.

5.2.2 ANALYSIS STAGE

Analysis of inspection data can involve measuring a range of parameters followed by decision-making based on comparing those measurements to a sometimes complex array of criteria that may vary with structure, location, manufacturing method, etc. A model should consider the influence of operator expectations, such as numerous previous inspections where no defects were detected. The potential implications of a false positive can also influence a decision.

5.3 AUTOMATED ANALYSIS MODEL

An automated analysis process is effectively a model in its own right. It can be used in combination with a range of trial data to determine its own reliability. The key is in supplying the right range of input data to exercise all aspects of the analysis process. Hence, what is needed here is a protocol for identifying and then testing all aspects of an automated analysis process by creating simulated trial data and supplementing it with real data.

5.4 REAL CRACK TRANSFER MODEL

A model is only required when the real defect differs from the artificial version in a way that is significant for the NDT method used. For example, a closed crack is significantly different to an EDM notch for ultrasonic propagation and interaction with the crack. However, other techniques, such as eddy-currents, can be much less sensitive to crack opening. If a scattered or diffracted signal is required from the crack in order to detect it, then it is necessary to model the crack’s surface roughness and the correct crack profile. It may be that the physics model used for the ultrasonic propagation includes the effects of the difference between simulated and artificial cracks, in which case no mark-up is required at the stage of this real-crack transfer model.

5.5 REAL STRUCTURE TRANSFER MODEL

Reliability considerations, when reading across from simulated structure to real structure, concern how the ultrasound interacts with structural features other than the defect itself. For example, the amplitude of reflections from the back of skin, or a defect at this depth, will depend on whether or not there is a second layer (spar, doubler or other sub-structure) bonded or sealed on. The signal from the fastener hole (and the defect), will depend on the interference fit of the fastener, as well as on any bonded sub-structure. It is therefore important to either use representative samples, or be able to model what the difference would be in terms of ultrasonic response in the simulated case versus the real case. Again, the ultrasonic propagation model may have already included structural and geometric effects, in which case this transfer function approach is unnecessary.

In real structures, shims sometimes exist between layers. They may be of uncertain thickness and may not be documented. The effect of these on the interpretation of the ultrasonic signals must be included in the model.

The presence of existing repairs on a structure, either from manufacture or in-service, can also complicate the interpretation of the NDI data. The repairs could be bonded or mechanically fastened, with various degrees of annunciation of their presence.

5.6 LARGE-AREA AND SHM MODEL

Many of the structural issues affecting NDT reliability are location-dependent, such as the local stress from an applied external load, the interference fit of each fastener, the integrity of bonds to sub structure, access to the potential defect site, and the presence of other reflectors that may masquerade as defects. Some of these effects, such as access and spurious reflectors, can be evaluated for each location and could be added as mark-ups to a_{NDI} and produced as a map of location-dependent contributions. Other effects, such as interference-fit of fasteners and bond-line integrity, cannot be easily mapped and a general mark-up in a_{NDI} has to be applied based on the statistical uncertainty due to these effects.

5.7 COMPOSITE MATERIALS MODEL

MoD is involved with in-service inspection of aerospace composite materials, but the range of different composites is very wide, from helicopter rotor blades through main wing skins and spars to honeycomb floor and ceiling panels. The range of NDT techniques applied is also diverse, including ultrasound, low-frequency vibration, thermography and shearography. In many cases, it is the defect size that primarily affects its detectability, so conventional POD methods do apply. However, these methods generate a value for a_{NDI} based on statistical methods and confidence levels – usually known as $a_{90/95}$ – the size of defect detected with 90% POD at a 95% confidence level. This assumes that there will be other opportunities to detect the 5% (or so) of missed defects after they have grown bigger under fatigue. It is not clear that such an approach is appropriate for defects that are not expected to grow under fatigue, resulting in a static load requirement [18-20] – the aircraft must survive with any undetected damage. There may never be a second chance to inspect a defect if the component fails after a defect has been missed.

In addition, the design of the structure will have incorporated assumptions about the detectable defect size and these will have been propagated through the testing and certification of the structures. Part of the certification is to show that the component can withstand Design Ultimate Load (1.5 x Design Limit Load) with any damage that is not ‘detectable’ at manufacture or during normal maintenance. Another certification requirement is that the component should withstand Design Limit Load (the maximum load that might be experience during service) with damage that might be missed by ramp maintenance personnel between flights. But how should these limits of detectability be determined?

These issues cast some doubt on the best method to qualify NDT for aerospace composite materials. A model could help to experiment with different qualification methods.

The comments recorded in Appendix C should be noted, especially the need to consider the influence of Lightning Strike Protection, eg ECF, and galvanic corrosion protection, eg glass cloth, which can complicate the interpretation of the inspection data.

6 CONCLUSIONS

This paper sets out the route for introducing, demonstrating and reviewing a protocol for model-assisted technique validation on new NDT capabilities.

Four parts are proposed to the required programme of work: 1) underpinning research and modelling for new NDT technologies, 2) drafting and reviewing of a standard governing the proposed protocol, 3) demonstration of the approach on one conventional and one new technology, 4) extension to composite materials. In order to make effective progress in each of these areas, a coordinated multi-party approach is required. This will include: an engineering doctoral (EngD) student through the UK Research Centre for NDE; pro-active involvement in the BINDT Aerospace Group, which has an objective to generate such a protocol; a funded programme of work lasting three to four years - competitively tendered; and the MASAAG NDT Working Group. The whole programme will be under the review and endorsement of the MASAAG membership, monitored by DSTL and with technical oversight provided by aerospace NDT experts at the University of Bristol.

Given the fields of expertise of the people and organisations already engaged in this programme, as well as both the short- and long-term needs for new NDT technologies in the military air domain, the obvious choice of NDT modality for the whole programme is ultrasound. Phased-array ultrasound has been identified as the new technology that will offer the most benefit to MOD.

The chosen application for staged trials of the protocol is the detection of cracks from fastener holes using angle-probe ultrasonic inspection, from manual swivel-scanning with operator-based analysis to automated phased-array scanning with automated analysis.

An extension to ultrasonic phased-array impact damage detection in composites will demonstrate the application of the protocol to composite materials where the link to structural integrity is significantly different.

The modelling EngD has commenced through the UK Research Centre for NDE (RCNDE) with world experts in phased-array ultrasound in the Ultrasonics and NDT Group at the University of Bristol. Phased-array ultrasound can lead to reduced detectable defect sizes, increased reliability and reduced false calls. Ultimately this will result in wider inspection intervals, extensions to service life, and future aircraft will be lighter and have enhanced performance.

7 RECOMMENDATIONS

It is recommended that a DSTL representative and the Engineering Doctorate student both join and actively participate in the Aerospace Group and Composites Group of BINDT in order to ensure a coherent approach to the establishment of a model-assisted technique validation protocol.

DSTL should put out an invitation to tender for the 3-4 year programme alluded to in this paper and the following statement of requirements and deliverables should be used.

7.1 STATEMENT OF REQUIREMENTS FOR FUNDED PROGRAMME

7.1.1 BACKGROUND

MASAAG Paper 119 proposed a mechanism for the introduction of new NDT capability based on model-assisted reliability assessment, removing the need for lengthy and costly POD trials. MASAAG Paper 122 sets out the route for introducing, demonstrating and reviewing a protocol for model-assisted technique validation on new NDT capabilities.

Four parts are proposed to the required programme of work: 1) underpinning research and modelling for new NDT technologies, 2) drafting and reviewing of a standard governing the proposed protocol, 3) demonstration of the approach on one conventional and one new technology, 4) extension to inspection of composite materials. In order to make effective progress in each of these areas, a coordinated multi-party approach is required. This will include: an engineering doctoral (EngD) student through the UK Research Centre for NDE; pro-active involvement in the BINDT Aerospace Group, which has an objective to generate such a protocol; the MASAAG NDT Working Group; and a funded programme of work lasting three to four years - competitively tendered, as described here.

The whole programme will be under the review and endorsement of the MASAAG membership, monitored by DSTL and with technical oversight provided by aerospace NDT experts at the University of Bristol.

7.1.2 OBJECTIVE

To create, draft and demonstrate a protocol for model-assisted NDT technique validation for military air-domain applications, through collaboration with other parties with either appropriate expertise and experience, or with a similar requirement (such as the civil aerospace sector), or objective.

7.1.3 SCOPE

The protocol will be generic in order to cover as wide a range of NDT methods as possible. Specific issues for large-area methods and structural health monitoring, as well as NDT of composite materials, automated acquisition, automated analysis and automated sentencing will also be addressed.

7.1.4 WP1 LITERATURE REVIEW

A literature review will be conducted to find and evaluate other relevant protocols, guidelines, models or software that may save time and effort in the programme; and to study, understand and summarise previous work in a report.

7.1.5 WP2 CONSULTATION EXERCISE

A consultation exercise will be carried out to ascertain requirements, scope and constraints for the protocol. An Industrial Advisory Group is to be established by the contractor with reference to MoD and this should meet at least once per calendar year to review progress and direction for the remainder of the programme.

7.1.6 WP3 PROTOCOL DRAFTING AND JUSTIFICATION

The successful tenderer will work with the Aerospace and Composites Groups of the British Institute of NDT and other interested parties to draft the new model-assisted technique validation protocol.

Significant parts of the protocol will require substantiation and validation in order to justify the approach taken. This work package will provide the means to undertake and report that justification work. In general the protocol itself would not contain the justification work, merely the implications of it to the protocol, but each element of technical advice should reference other work justifying it with evidence, or should refer to an Annex with that technical justification and evidence.

It is anticipated that contractor attendance will be required at four BINDT Aerospace Group meetings and four BINDT Technique Validation Working Group meetings per year, for the duration of the project. In addition, the contractor will attend meetings of the chosen standards organisations and respond to correspondence.

7.1.7 WP4 TRIALS

Ultrasound is the chosen NDT modality for demonstrating the new protocol because Phased-array ultrasound has been identified as the new technology that will offer the most benefit to MOD in the short and medium term.

The chosen application for staged trials of the protocol is the detection of cracks from fastener holes in metals using angle-probe ultrasonic inspection, from manual swivel-scanning with operator-based analysis to automated phased-array scanning with automated analysis. An extension to normal-incidence ultrasonic mapping of composites for accidental impact damage will also be required.

A series of staged trials are required for illustrating the effectiveness of the technique validation protocol across its breadth of inspection scenarios. For this reason, the following stages have been defined.

1. Manual Angle-Probe Ultrasonic Technique
2. Array-Probe Manual Sector-Scan Inspection
3. Array-Probe Manual Lateral Scan Inspection
4. Full Matrix Capture
5. Automated Acquisition
6. Automated Analysis

These are described individually in sections 4.3.1 to 4.3.6 of MASAAG paper 122.

Finally, a trial will be required for inspection of a composite structure for in-service impact damage, described in section 4.4 of MASAAG Paper 122..

7.2 DELIVERABLES

A series of six-monthly deliverables should be provided to MoD and distributed to all participants to provide adequate visibility of progress and the opportunity for feedback from MoD and other collaborators. These should include reports on the trials and new drafts of the protocol after each trial as follows:

1. First draft of protocol prior to any trials.
2. Report on trial and second draft of protocol following trial with Manual Angle-Probe Ultrasonic Technique.
3. Report on trial and third draft of protocol following trial with Array-Probe Manual Sector-Scan Inspection.
4. Report on trial and fourth draft of protocol following trial with Array-Probe Manual Lateral-Scan Inspection.

5. Report on trial and fifth draft of protocol following trial with Full Matrix Capture Inspection.
6. Report on trial and sixth draft of protocol following trial with Automated Acquisition.
7. Report on trial and seventh draft of protocol following trial with Automated Analysis.

Evidence shall be delivered that the protocol has been applied to each of the staged trial applications. This should include a summary of the changes made to the protocol as a result of the trial.

REFERENCES

1. Smith, R.A., Birt, E.A., Phang, A.P., Allen, B.P. and Williamson, C, “Mechanism for introduction of new non-destructive testing capability”, MASAAG Paper 119, 2012.
2. MIL-HDBK-1823A. “Nondestructive evaluation system reliability assessment,” United States Department of Defence, April 2009.
3. Harding, C, Lindgren, E, Mandache, C, Knopp, J, Fahr, A and Khan, M, “Model-based methods for reducing costs associated with POD studies” TTCP Technical Report TTCP/MAT-TP-5/7/2008, May 2009.
4. Harding, C.A., Hugo, G. R. and Bowles, S. J., “Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes”, 32nd Annual Review of Progress in Quantitative Nondestructive Evaluation, 2005. Brunswick, Maine.
5. Harding, C. A., Hugo, G. R. and Bowles, S. J., “Automated Ultrasonic Inspection for Crack Detection at F-111 Lower Wing Skin Fastener Holes”, 12th Asia-Pacific Conference on Non-Destructive Testing, 2006, New Zealand.
6. Hugo, G. R., Harding, C. A. and Bowles, S. J., “Reliability Validation of Automated Ultrasonic Scanning for Detection of Fatigue Cracks at Fastener Holes”, in 9th Joint FAA/DoD/NASA Conference on Aging Aircraft, 6-9 March 2006, Atlanta, GA., USA.
7. Hugo, G. R., Harding, C. A. and Bowles, S. J., “Model-Assisted Probability of Detection Validation of Automated Ultrasonic Scanning for Crack Detection at Fastener Holes”, in 10th Joint FAA/DoD/NASA Conference on Aging Aircraft, Palm Springs, CA, USA, 16-19th April 2007
8. Harding, C. A. and Hugo, G. R., “Overview of DSTO work in POD modelling & Statistical Analysis Methods”, MAPOD Working Group meeting, 16 November 2007, Las Vegas, NV, USA.
9. Harding, C. A. and Hugo, G. R., “Overview of DSTO work in POD modelling”, MAPOD Working Group meeting, 14 November 2008, North Charleston, SC, USA.
10. Harding, C. A., “Methods for Assessment of Probability of Detection for Nondestructive Inspections”, PhD thesis, Department of Mathematics and Statistics, University of Melbourne, June 2008.
11. Harding, C. A. and Hugo, G. R., “Practical Reliability Validation for Nondestructive Inspections and Structural Health Monitoring Technologies”, Aircraft Airworthiness and Sustainment Conference, August 2010.
12. Smith, R. A., Edgar, D., Jones, L. D. and Percivall, D. M., "An Ultrasonic Solution For Second-Layer Crack Detection", Insight - The Journal of The British Institute of NDT, Vol 47, No 2, pp 81-84, Feb 2005
13. Smith, R. A., Edgar, D. and Jones, L. D,, "Rapid second-layer crack detection using phased-arrays and automated analysis", Proceedings of the 8th Joint DoD/FAA/NASA Conference on Aging Aircraft, Palm Springs, Jan 2005.
14. Nelson, L.J, Brown K, Young A, Jones L.D and Smith R A, "Ultrasonic detectability of potentially closed cracks from cold-worked holes under loaded conditions." Insight - The Journal of The British Institute of NDT, Vol 50, No 2, pp 78-87, Feb 2008.
15. Whittle, M.J., “A review of worldwide practice and experience in the qualification of ultrasonic inspections of nuclear components over the past two decades.” Insight - The Journal of The British Institute of NDT, Vol 51, No 3, pp 140-150, 2009.

16. “Non-destructive testing. Methodology for qualification of non-destructive tests”. PD CEN/TR 14748:2004, BSI, 22 November 2004.
17. “European Methodology for Qualification of Non-destructive Testing – Third Issue”. European Network for Inspection and Qualification, ENIQ Report No. 31, EUR 22906 EN, August 2007.
18. Foreman, A. Jones, D. and Greenhalgh, E, “A review of the damage tolerance capability of Typhoon carbon fibre composite structure.” QinetiQ Working Paper No. QinetiQ/FST/WP032183, Jan 2004, UK RESTRICTED.
19. Razi, H. and Ward, S., “Principles for achieving damage tolerant primary composite aircraft structures.” 11th DoD/FAA/NASA Conf. On Fibrous Composites in Structural Design, Fort Worth, TX, August 1996.
20. Bowen, R, Bleay, S, Greenhalgh, E, Lord, S, Mew A and Willows, M, “Certification of Composite Structures with Impact Damage: A Review,” DERA Technical Report DERA/MSS3/CR980550/1.0, 1998

Appendix A: Engineering Doctorate

The following is a definition of the EngD project funded by the UK RCNDE and DSTL. The student is Mr Alex Ballisat who commenced the 4-year EngD in April 2014.

Objective

The project is aimed at facilitating the introduction of new NDT technologies into the military (primarily Air) arena through model-assisted technique validation methods.

Background

Qualification of an NDT work instruction for use in the field requires the adoption of an accepted sensitivity to defects - usually expressed as a Minimum detectable Defect Size. Conventional techniques have accepted sensitivities based on years of experience, anecdotal evidence and some probability of detection (POD) trials. But new technologies lack this historical evidence and POD trials are notoriously expensive and time consuming. In addition, there is no experience of conducting such trials in the military. The result is that no new NDT technologies have been introduced in MoD in the last 15 years. MoD is about to embark on a 3 year programme to develop a protocol for model-assisted POD and demonstrate its use on both conventional and 'new' technologies. This programme will be contracted out in summer/autumn of 2014 after an open tendering process. In addition, the Aerospace Group of the British Institute of NDT (BINDT) is engaged on a programme of work to draft a standard for technique validation along these lines and based on the ENIQ report on this subject. Any successful standard or protocol must be backed up by good scientific understanding and be based on scientifically proven methods. This EngD is intended to provide that scientific backing.

Principle of the proposed solution

Any NDT work instruction comprises several interconnecting processes, each of which can potentially be studied independently in terms of their reliability. In principle a new technique could have its overall reliability determined by some combination of the reliabilities of each of the interconnecting processes. Some processes will lend themselves to scientific determination of reliability, whilst others will require a combination of experiment and modelling, and others can be modelled completely and just require that model to be validated experimentally. The method of combining these reliabilities will be a crucial element of the research. All of this normally comes under the broad heading of Model-Assisted Probability of Detection (MAPOD), but Model-Assisted NDT Reliability might be more appropriate. Such modelled approaches can yield benefits in optimisation of techniques and work instructions prior to their validation.

Research challenges

'Reliability' is still poorly defined, but is now thought of not just as 'sensitivity' to defects, but also 'specificity' - the likelihood of erroneous positive responses. This whole area is poorly covered in the literature and there is still no definitive single measure of reliability that can be unambiguously linked to the structural integrity of a component. Hence it will be important to understand and establish this link to structural integrity during the project.

Various models have been developed for NDT methods and a few protocols for a 'transfer function' approach to MAPOD have been developed and worked through. However, there is no generic framework or accepted broadly applicable protocol. This will have to be developed and then tested.

Finally, there will be gaps in the availability of suitable models. In particular DSTL are interested in phased-array ultrasound and the implications in terms of assessment of reliability if they introduce it to inspections currently undertaken using more conventional methods. Building on the expertise at the University of Bristol on phased-array ultrasound, it will be necessary to assess current models and develop new ones where necessary.

Collaborations

Within MoD: DSTL, NAS 1710 (Navy) and 71(IR) Sqn (RAF)

Institutes: BINDT Aerospace Group, ADS NDT SIG
Industry: AMEC (IVC), TWI (NDT Validation Centre), QinetiQ Ltd, and whoever wins the MoD programme on MAPOD.
International: DSTO Melbourne, AFRL (UASF) Dayton, AANC (Sandia National Labs) Albuquerque, NRC Canada, NRL (Netherlands).

Appendix B: MIL-HDBK-1823 Treatment of MAPOD

MAPOD is defined in MIL-HDBK-1823 as “methods for improving the effectiveness of POD models that need little or no further specimen testing” and is dealt with in Appendix H of the handbook. MAPOD is mostly appropriate for inspection methods that produce a quantitative signal, *â* and *â vs. a* analysis methods are employed. The original *â vs. a* model can be modified either by the use of experimental results (e.g. comparing the responses of fatigue cracks as compared to EDM notches) or by the application of physics–based models. The handbook notes that, as of early 2007, there were three documented MAPOD projects reported in the open literature. Figure B-1 (below) uses a flow diagram to illustrate the method.

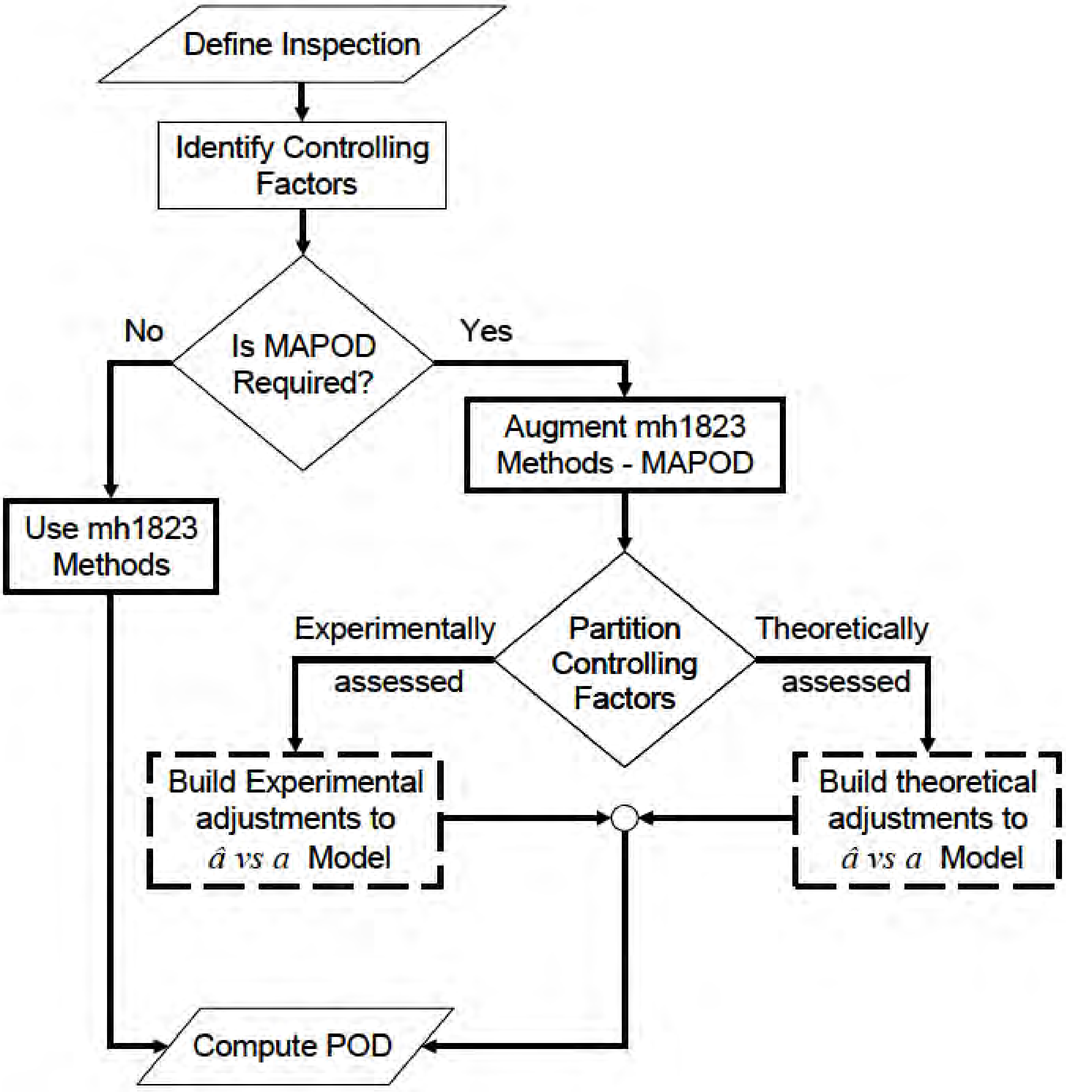


Figure B-1. Model-assisted POD model building process (after MIL_HDBK-1823A [2]).

Appendix C: Comments from MASAAG members

A draft of this Paper 122 was circulated to MASAAG members on 24 July 2014 and the following table records relevant comments received and the response from the author in each case. The current version of Paper 122 has been amended accordingly.

Comment	Response
I only have one comment and that's relating to terminology and definitions. The author has referred to 'NDT Techniques' but this could be ambiguous and it is not clear if he means a subset of a method or a written Instruction, especially as the MOD NDT community tends to use it in the latter context. BS EN 4179 defines the differences and should be used to avoid confusion.	This document has been checked and modified to use BS EN 4179 definitions and this has been explained in a new paragraph in Section 1.3. A 'technique' is a category within a method; a 'work instruction' is a specific inspection.
I agree that phased-array ultrasonic inspection is a good choice for the new technology example. It is already widely used in industry.	No change required.
In multi-layer structures (either metallic or mechanically assembled composite laminates) the effect of assembly shims should be included in the programme. These shims are likely to be tapered, different material depending on the gap to be filled, and unique to each assembled structure. Our experience is that these shims can complicate the interpretation of the NDI data.	Agreed that shims will be a factor considered in the models and demonstrators in the programme. This has been added to Section 5.5.
The presence of Lightning Strike Protection, eg ECF, and galvanic corrosion protection, eg glass cloth, can complicate the interpretation of the NDI data.	For the composites application, this should be part of the model and demonstration. Section 5 has been amended accordingly.
The civil aircraft certification approach for composite structures is generally now in accordance with AC 20-107B, which focuses on impact damage being visually detectable, with a link between the maintenance activity detecting any damage, and the structural residual strength requirement. As recognised in the paper, NDI is typically for quantitative purposes.	No change required.
The approach to meeting the intent of AC 20-107B (composites) can vary between OEMs. In particular the use of energy cut-off for Cat 1 damage (BVID) will be different, therefore the inspection requirements may vary between OEMs.	These issues of compliance are important. In this paper we are concerned with technique validation appropriate to compliance - allowing different approaches but the same NDT validation methodology.
The presence of existing repairs on a structure, either from manufacture or in-service, can also complicate the interpretation of the NDI data. The repairs could be bonded or mechanically fastened, with various degrees of annunciation of their presence.	Yes, the presence of repairs or modifications would be a consideration in a model-assisted approach to technique validation. Added to Section 5.5.
PoD Curves – Inspection Specifivity and Accessibility, and Operator Expectation. PoD curves developed from lab work generally reflects that achievable when an inspector is in comfortable surroundings, on a relatively small sample, with good access, and one for which he/she expects will have a	Important issues, but these are exactly what a human factors model should allow for. What has been added to the Figure 1 flow diagram is a human factors model

flaw(s) in it somewhere. The PoD achieved when one is asked to inspect a large number of fasteners or inspect a general area, asked to inspect hard to reach structures or in an uncomfortable position, or asked to inspect an area where the inspector is used to getting nil-findings, is significantly lower than the lab example. One would expect a protocol to address this issue – I'm assuming that this would be incorporated into the Human-factors model shown in Figure 1 of the Draft, so perhaps it could just be noted that the human factors model should account for such issues?	for acquisition as well as analysis. Also, Section 5 now has a specific Human Factors sub-section, covering both acquisition and analysis stages.
PoD Curves – Lab variability. The amount of PoD variability seen lab-to-lab can be very large (cf. NTIAC's database DB-97-02). Would there be an intention for the protocol to address this? If not, would there need to be conservatism inserted into the PoD curves to account for this effect? Either way this could be noted as a requirement for the protocol.	This variability is a result of all the factors that will be addressed by the models and trials that make up a realistic MAPOD study. The MAPOD protocol should predict such variability by addressing its sources. Hence there is not a need to include such variability explicitly, but part of the validation of the protocol should be to check that the actual lab variability experienced lies within the model-predicted bounds.
PoD Curves – Use of PoD within existing Acceptable Means of Compliance. If one wants to develop a PoD curve, then ideally one needs to understand how it is intended to be used. To illustrate different ways of use – Simulation methods vs Fixed 'inspectable flaw sizes': Example A). In the past, Def Stan Leaflets suggested the use of 'simulation methods' in damage tolerance calculations whereby it was assumed that inspections would begin whilst the crack was still uninspectable and then every time an inspection occurred and the crack was larger then the probability of detection would increase. An overall level of safety could then be defined and an inspection interval defined that would provide an acceptable joint probability of detection over the multiple inspections. My understanding is that Boeing Commercial still use this type of assessment in IDTAS. Example B) On the other hand almost all other AMCs these days, including current Def Stan, define an inspectable flaw size (that being a flaw that is 'difficult to miss'; sometimes defined as 90% PoD and sometimes with a set confidence level (e.g. 95%)), and then suggest a number of inspection intervals from detectable to critical. What I'm trying to say here is that this illustrates that depending on what method one is using will drive details of what they need from the PoD curve. Simulation methods need accuracy at low PoD whilst standard methods need accuracy at high PoD. This in turn may drive the mechanics of the mathematics behind the curves, as different curve formulations may suit different methods. Therefore it may be worth the Protocol explicitly stating the intended use of the PoD curves, or stating that the use should be decided as part of following the Protocol.	This protocol is intended to provide guidance about how best to meet the Acceptable Means of Compliance requirements over a range of applications and should include advice on the best means of determining reliability in each category. It is true that several requirements documents assume a defect growth curve is known but this is not appropriate for situations where defects do not grow under fatigue, for example. This is one of the reasons for including a composite inspection - this is currently a static strength problem, not a fatigue-induced growth problem.

Demonstrator issues. I would have assumed that one of the key aspects of the protocol is to establish how one, when attempting to validate a MAPoD, would: decide whether to use man-made notches or fatigue flaws for validation (i.e. Does one use EDM notches, or fatigue cycle EDM notches into cracks and then remove the notches?); generate the man-made or fatigue flaws for the test samples; confirm true final flaw size in the test samples (if using fatigue flaws); double-blind the labs doing the inspections; ascertain the true number and location of flaws when creating fatigue flaws in a multiple fastener stack-up (if using fatigue flaws). If this is already covered by an existing specification or best practice guide, then the easiest thing may be to just reference that source.	Yes, this protocol will cover those things and can refer to other specifications if they exist, but the main aim is to avoid having to continually reassess the differences between real and simulated defects - a model based on such experimental work will be able to predict the difference between, say EDM notches and realistically grown fatigue cracks. Section 5.4 covers the modelling of the differences between real and simulated defects.
I note that there doesn't seem to be any reference to the National Physical Laboratory (NPL) as an 'interested body/organisation' or work they may have done in this area. A quick look at their website shows they have an interest in NDT/NDE, and they may have some research (and who knows even funds) to contribute to this, It may be that the author has considered them already, and they are probably represented on some of the bodies identified in the paper.	Agreed that NPL would be a useful addition to the list of potential consortium members.
This is probably for MASAAG consideration rather than for the paper itself: the paper will hopefully provide a protocol with supporting evidence, the next question is: will a standard be written on the basis of the paper, and if so who authorises it (sounds like the National NDT body is best placed) and where (if at all) in the MRP does it get referenced/called out to authorise it's use by the likes of 1710NAS etc. I can see such a standard being referenced as AMC or guidance in some of the current 970 requirements (eg Part 1, Section 4), but the move to a primarily to a cert spec for 970 may mean reference to NDT techniques aren't suitable in 970. I know it's a bit in the future, but defining a position now will help focus the outputs of the task.	Agreed that a discussion early on about the future path for, and usage of, this protocol would result in a document that is more appropriate and fit for that purpose. The potential for Def Stan 970 to reference this protocol has been added.
Obviously a comprehensive protocol! I notice it states "Development of a mechanism for acceptance of new NDT capability in the air domain" page 43 (Item 3). Is this purely an MoD based piece of work or is for a wider audience? I only ask because I cannot see where it states that it will satisfy EN4179, albeit I assume it doesn't really need to given the title above? Other than that I have no other comments.	This is for MOD, but may be incorporated into a wider-scope best-practice document being developed by BINDT Aerospace Group, or a standard. EN4179 covers personnel certification, not technique validation, but it does require the Level 3 to have determined the validity of the technique, so the proposed protocol provides a means of compliance for the Level 3 to use.

REPORT DOCUMENTATION FORM

1. Originators Report Number incl. Version No MASAAG Draft Paper 122

2. Report Protective Markings

UNLIMITED

3. Title of Report

Development of a mechanism for acceptance of new NDT capability in the air domain

4. Title Protective Markings incl. any Caveats UNLIMITED

5. Authors Prof Robert A Smith

6. Originator's Name and Address	7. Task Sponsor Name and Address
Prof. R A Smith, Dept. Mechanical Engineering, Queens Building, University Walk, Bristol, BS8 1TR	Dr Steve Reed Fellow Structural Integrity and Ageing Ac DSTL Porton Down

8. MOD Contract number and period covered DSTLX-1000087982 19/01/14 – 31/03/15

9. Other Report Nos.
None

10. Date of Issue	11. Pagination	12. No. of References
October 2014	viii + 30 Pages	20

13. Abstract (A brief (approximately 150 words) factual summary of the report)

In 2011, the MASAAG recognised difficulties in introducing new NDT methods into the air domain. MASAAG Paper 119 (2012) identified the primary reason as the lack of a historical track record on which to validate new capability. Validation of conventional NDT was based on experience, inspection evidence and engineering judgement. The accepted validation for new techniques – a probability of detection (POD) trial - was generally too costly. Paper 119 proposed using model-assisted POD (MAPOD) to remove the need for full trials. The objective for a new programme of work is to draft, demonstrate, review and introduce a protocol for MAPOD. Four parts are proposed to the programme: 1) underpinning research/modelling, 2) drafting the protocol, 3) demonstration of the approach, 4) extension to composites. A multi-party approach is required, to include: an EngD student; pro-active involvement in the BINDT Aerospace Group; a commercial contract - competitively tendered; and the MASAAG NDT Working Group. The programme will be under the review and endorsement of the MASAAG, monitored by DSTL, with technical oversight by the University of Bristol. Demonstration of the protocol will be for the detection of cracks from fastener holes using angle-probe ultrasonic inspection, from manual swivel-scanning with operator-based analysis to automated phased-array scanning with automated analysis. Ultimately this will result in wider inspection intervals, extensions to service life, and future aircraft will be lighter and have enhanced performance.

15. Keywords/Descriptors (Authors may provide terms or short phrases which identify concisely the technical concepts, platforms, systems etc. covered in the report).

MASAAG, Non-destructive Testing, Reliability, Structural Integrity.