STANDARDISED PROCEDURES FOR ULTRASONIC INSPECTION OF POLYMER MATRIX COMPOSITES

W.R. Broughton, M.J. Lodeiro, G.D. Sims, B. Zeqiri, M. Hodnett, [1]
R.A. Smith and L. D. Jones [2]
[1]*National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK*
[2]*Defence Evaluation and Research Agency, Farnborough, Hampshire, GU14 6TD,UK*

SUMMARY: A wide range of inspection techniques are available for quality/process control and in-service monitoring of composite structures, of which ultrasonic C-scan inspection techniques are the most widely used. At present, there are no universally accepted standards or procedures for ultrasonic C-scan inspection of composites and, as a result of this absence, the reliability and traceability of this method have been limited. In response to this need, a programme "Standardised Procedures for Ultrasonic Inspection of Polymer Matrix Composites" was initiated. The programme has produced three procedures: for operating C-scan equipment, calibrating ultrasonic transducers and producing reference panels with simulated defects. This paper provides an overview of the research objectives and activities of the programme, discusses the current status of standardisation of ultrasonic C-scan procedures, the working procedures developed within the programme, the scientific output and the results of two national (UK) round-robin exercises.

KEYWORDS: Composite materials, ultrasonic inspection, non-destructive evaluation, standards.

INTRODUCTION

Composite materials are used in safety-critical components where they need to satisfy stringent requirements for safety and quality. Gaining the levels of confidence required for these applications has relied on the development of non-destructive evaluation methods for characterising these materials. Ultrasonic C-scan inspection is the most widely used of these techniques. C-scanning is used to detect, measure and characterise a wide range of manufacturing and in-service defects in composite materials and is routinely used in the aerospace industry, often using large and expensive facilities with commensurate operating costs. However, the reliability and traceability of the method have been limited as there are no universally accepted national or international standards or procedures for ultrasonic C-scan inspection of composites. Current standards are directed towards the inspection of metals. Companies within the aerospace/defence industry undertake inspections to different procedures set down by major aerospace companies or routines developed in-house.

Several benefits could be expected from the availability of standard procedures, including:

- *Improved safety and quality assurance*
- *Reduced production and maintenance costs*
- *Reduced risk of human error*
- *Optimisation of manufacturing and processing methods*
- *Improved confidence in long-term performance*

In response to this industrial need, the research programme "Standardised Procedures for Ultrasonic Inspection of Polymer Matrix Composites" was initiated. The project, led by the Centre for Materials Measurement and Technology (CMMT) at the National Physical Laboratory (NPL), was sponsored by the UK Department of Trade and Industry (DTI) under the Commercial Aircraft Research and Development (CARAD) initiative. The programme was supported by both the Centre for Mechanical and Acoustical Metrology (CMAM) at NPL and the Structural Materials Centre at the Defence Evaluation and Research Agency (DERA), Farnborough. An Industrial Advisory Group (IAG) consisting of ultrasonic test equipment manufacturers/suppliers and end-users ensured industrial relevance and applicability.

The programme was designed to identify and develop standardised procedures for the ultrasonic inspection of composite structures, with the primary aim of placing C-scan techniques on a sound and traceable basis. Individual objectives were:

- *To develop basic "operational" procedures, possibly through harmonisation of existing methods*
- *To develop calibration procedures for ultrasonic transducers*
- *To assess the effects of the "acoustic properties" of the overall system on quantitative measurements and make recommendations on system tolerances*
- *To establish standard procedures to simulate representative defects and produce reference blocks*
- *To consider methods for porosity measurement*

This paper provides an overview of the research objectives and activities of the programme, discusses the current status of standardisation of ultrasonic C-scan procedures, the working procedures developed within the programme, the scientific output and the results of two national (UK) round-robin (R-R) exercises.

REVIEW OF INDUSTRIAL PRACTICES AND REQUIREMENTS

A review was carried out to identify current industrial practices and requirements. The assessment covered procedures/standards for the operation and calibration of C-scan equipment, and methods used for producing reference (calibration) panels incorporating representative production defects. Procedures applicable to quality/process control, manufacturing acceptance and in-service damage assessment were collected from the IAG members and other sources. The result of the assessment was used to guide the experimental programme and to provide the basis for the draft procedures.

The areas covered in the assessment are summarised below.

Operational Procedures: Covered the ultrasonic set-up used, system parameters, transducer type, collimators, couplants and wetting agents and ultrasonic signal attenuation.

Calibration Procedures: Considered frequency spectrum analysis, beam profiling, focal distance and effective focal zone measurement techniques and electronic characteristics of ultrasonic C-scan equipment.

Reference defects and materials: Identified types of defects encountered and materials and methods used by industry for simulating manufacturing defects and service-induced damage.

Porosity: The assessment considered various ultrasonic attenuation measurement techniques used for determining porosity levels. Porosity is defined as a concentration of the microscopic voids that are entrapped in the resin, within and between fibre layers. Although there are a number of techniques that can be used to measure relative attenuation, none of these can be relied upon to provide a single, unambiguous measurement of the porosity level. The size distribution and shape of these voids cannot be quantified using current ultrasonic techniques. For most quality control requirements, it is sufficient to relate relative ultrasonic attenuation to an acceptance standard (corresponding to a maximum acceptable porosity level) rather than establish the actual percentage of voids in the material. A level of 1% porosity is generally accepted for most pre-impregnated composite structures. This approach is universal, although accurate porosity level measurements would be preferable. Difficulties encountered in controlling the introduction of porosity make the production of reference materials with known porosity levels impractical. As a result, the approach generally recommended for the quantitative assessment of void content is image analysis.

CURRENT STATUS OF STANDARDS AND PROCEDURES

It was apparent from contact with industry, that no international or national standard procedures were available for ultrasonic C-scan inspection of composite structures. This situation remains unaltered. Many contributors to the assessment were using either 'in-house' procedures or procedures specified by customers, the majority of which involved the use of some form of reference material containing typical defects. A number of companies within the aerospace/defence industry are currently using either the McDonnell Douglas Process Standard DPS 4.738-2 [1] or, to a lesser extent, Boeing Aircraft Company Process Specification Number BAC5980 [2]. Both documents specify process requirements and provide instructions for the ultrasonic inspection of composite structures.

The scope of these procedures covers a wide range of ultrasonic C-scan applications; from contact to immersion probes, with straight or angled beams, for a frequency range of 0.4 to 20 MHz. The procedures are suitable for examining flat panels and honeycomb sandwich constructions for single- and double- through transmission, and pulse-echo modes of operation. Only a few standards relating to calibration of transducers and associated electrical drive systems were directly relevant to the ultrasonic C-scan inspection of composites, such as the McDonnell Douglas document and ASTM E 1065-92 [3]. The latter is a "guide" containing detailed experimental evaluation techniques, but no tolerances. It considers the transducer in isolation, rather than the transducer/drive combination. The McDonnell Douglas document considers systems as a whole, with few specifications for transducers alone. It is the only standard that directly addresses the C-scan inspection of composites.

ASSESSMENT OF IN-HOUSE C-SCAN PROCEDURES

A stepped reference panel manufactured from carbon fibre-reinforced epoxy was circulated to a number of companies within the UK to compare the systems currently in use, prior to standardising on a common procedure. The objective of the R-R exercise was to identify the key parameters which influence inspection quality and to establish the degree of control required to obtain suitable repeatability and accuracy. The reference panel (Fig. 1), designed and produced at NPL, contained circular and square defects of three different sizes located near the upper and lower surfaces of the laminate and at the mid-plane. The panel, which was 360 mm long and 230 mm wide, contained five discrete steps of different thicknesses (1 mm or 16 ply increments) for attenuation measurements. A quasi-isotropic laminate configuration was used. The lay-up per step was $[45^o/0^o/-45^o/90^o/90^o/-45^o/0^o/45^o]_S$. The panel had a smooth back surface with the front surface partitioned equally into smooth and rough finishes in order to assess the effect, if any, of surface finish on attenuation measurements.

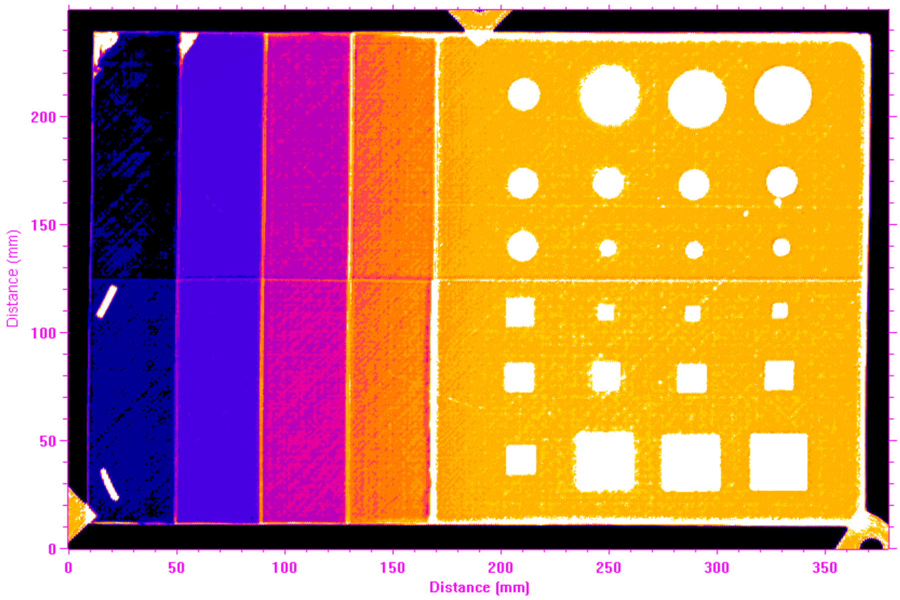

Fig. 1: C-scan image of stepped reference panel with defects (courtesy of DERA).

Artificial defects (representing delaminations) 6.35, 12.7 and 25.0 mm in size were fabricated using two layers of 50 µm thick poly-tetrafluroethylene (PTFE), sealed around the edges with heat-resistant tape to ensure and maintain an air gap. The artificial defects were placed between the 2nd and 3rd plies (right column in Fig. 1), at the mid-plane (second column from right in Fig. 1) and between the 38th and 39th plies (second column from left in Fig. 1) in the 5 mm section of the panel. This was to check the resolution of inspection systems as a function of through-thickness location. The combined effect of the highly attenuative PTFE film and the entrapped air produced a well defined acoustic barrier, preventing almost the entire ultrasonic signal from being transmitted through the artificial defect. Square and circular shaped defects were included to determine the effect, if any, of defect geometry on detection/measurement accuracy. The frequent accidental inclusion of single ply release film in laminates warranted the presence of single layers of square and circular shaped release film, positioned within the reference material at three different depths. The inserts, 12.7 mm in size, were located along the left column in Fig. 1. The rough finish on one half of the stepped surface of the panel was produced by leaving the bleed cloth in place during the curing cycle.

The reference panel was inspected by nine establishments (including NPL and DERA). Modes of inspection included single- and double-transmission, and pulse-echo (contact and immersion). Focused and unfocused (with and without collimators) transducers were used at various stand-off distances from the panel. No attempt was made to control the inspection parameters used by the participants in this initial R-R exercise.

Differences in inspection parameters, scale and colour index (i.e. relative attenuation levels) of C-scan images made quantitative comparisons difficult, if not impossible in some cases. Despite the differences in inspection technique, the shape and size of the defects as recorded by the different participants were generally similar. A few participants in the R-R exercise measured the size and area of the defects according to the 6 dB drop method developed at DERA [4, 5]. The -6 dB defect area is defined as the area of a single defect over which the ultrasonic reflection amplitude is attenuated by more than 6 dB of the maximum signal reflected from either the defect or the back surface, or a reflector plate behind the specimen, depending on the signal gating in use.

The following observations were made from the R-R results:

- *All inserts were detected by the participants with the position of the defects being identical.*
- *The apparent defect size, when measured to the edge of the insert, was similar for all participants, independent of the size and through-thickness location of the insert.*
- *Differences in apparent defect size was dependent on the inspection technique and inspection parameters. It was not possible to reliably quantify those differences from visual inspection of the C-scan images.*
- *The apparent defect size was larger for C-scan images obtained using an unfocused transducer without a collimator.*
- *Visual measurements from C-scan images invariably resulted in larger defect size measurements compared with the -6 dB method.*
- *Relative attenuation measurements varied between participants. This was most probably due to differences in calibration procedures.*
- *Uncertainty in defect size increased with decreasing defect size.*

The results of the R-R exercise clearly supported the need for standardised inspection procedures, and the identification and quantification of sources of uncertainties in both attenuation and defect size measurements. Difficulties were encountered in interpreting the C-scan results in a quantitative manner (other than obvious assessment of visual similarities) due to insufficient data being recorded/supplied. This can be attributed to a basic deficiency in the detailed requirements specified by in-house procedures.

TECHNICAL DEVELOPMENT PROGRAMME

Attenuation measurements (Fig. 2) were carried out on a range of materials, these included Perspex^{TM}, stainless steel, glass-fibre woven fabric composites and the carbon-fibre reinforced reference panel. The objective was to produce a method for determining absolute attenuation that was independent of the measurement method for a given frequency. This work involved identification and quantification of systematic uncertainties in amplitude and defect size measurements due to diffraction and refraction effects, peak-frequency downshift and non-linear propagation in water [5]. A procedure was developed that enables the bulk attenuation coefficient (dBmm^{-1}) to be calculated for the frequency used and as a function of frequency (dBmm^{-1}Hz^{-1}) [6].

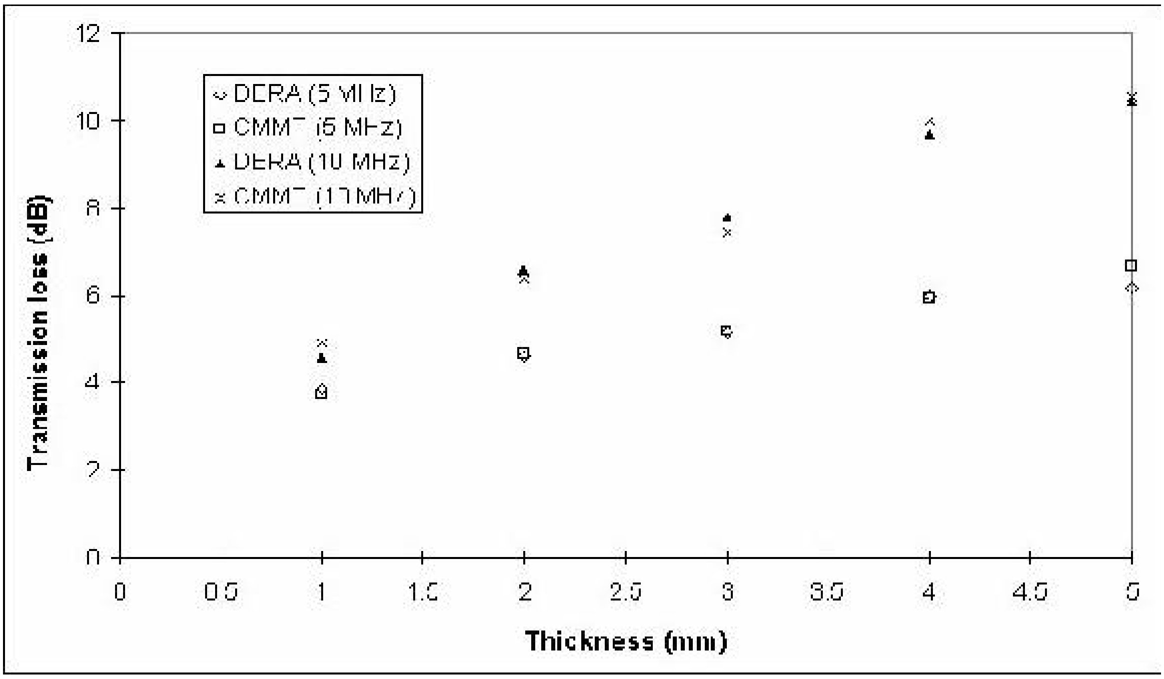

Fig. 2: Transmission loss vs thickness for stepped CFRP laminate.

Calibration procedures were developed for non-destructive evaluation (NDE) ultrasonic transducers using hydrophones and pulse-echo methods (i.e. spherical and flat targets). The experimental assessment considered the effect of collimators on beam parameters. A series of tests were carried out to evaluate the effect of changing collimator aperture size, thickness and collimator-transducer stand-off distance. The effect of placing a PTFE collimator in front of an unfocused transducer is shown in Table 1. The results demonstrate that for a 10 MHz transducer with a crystal diameter of 10 mm, a 4 mm diameter aperture reduces the -3 dB bandwidth (as measured using membrane hydrophones) by a factor of 3 and the position of the last axial maximum (Yo^{+}) by an order of magnitude. Ultrasonic wave properties (i.e. attenuation and phase velocity) were measured for a number of isotropic and anisotropic materials in order to assess the effect of dispersion, frequency downshift and non-linear propagation on ultrasonic measurements. The introduction of a collimator with an aperture smaller than the crystal diameter of the transducer results in a cleaner and more symmetric beam, albeit at the expense of the beam energy. The results from these investigations have been included as appendices in the draft calibration procedure.

Table 1: Collimator effect on 10 MHz frequency/10 mm diameter transducer.

Parameter	Uncollimated	4 mm Diameter Collimator
Position of last axial maximum ,Yo^+ (mm)	140	15
-3 dB beamwidth (mm)	3.3	1.0

WORKING DRAFT PROCEDURES

Three working draft procedures for ultrasonic C-scan inspection of composite structures were produced. The procedures, which are listed below, were supported with an extensive test programme. The results of the supporting technical programme, summarised in the following section, are described in a collection of papers in the January 1998 edition of the Journal INSIGHT "Non-destructive Testing and Condition Monitoring" [5-9].

Part 1 - Operational Procedure

This draft specifies three methods for ultrasonic C-scan inspection of fibre-reinforced plastic composites.

Method 1 - Pulse echo (both immersion and contact).
Method 2 - Single through-transmission (both immersion and water-jet).
Method 3 - Double through-transmission.

The methods specified in this draft are applicable to transducers operating in the frequency range 0.5 to 10 MHz.

For each of these three methods of operation, three different measurements are considered:

- *Relative attenuation measurement by comparison with a reference standard scanned alongside the test component. This type of measurement may be used for defect detection and characterisation.*
- *Absolute attenuation measurement which could lead to the determination of bulk attenuation - a property of the specimen.*
- *Defect sizing of planar defects in laminates.*

Three different methods of coupling the ultrasound into the composite are covered: water tank immersion systems, water-jet systems, and contact scanning. The methods are suitable for use with carbon and glass fibre-reinforced thermoset and thermoplastic matrix composites incorporating unidirectional or non-unidirectional reinforcements in either a continuous or discontinuous format; including woven fabrics.

The draft was based on procedures collected from both UK and international industrial users. Although this technique is initially targeted primarily at aerospace-type materials, particularly flat laminates, a wider use is foreseen.

Part 2 - Transducer Calibration Procedure

This draft document specifies test methods for determining the important properties of immersion ultrasonic transducers (used for the C-scan inspection of composite structures according to the specifications in Part 1). The document specifies test methods for both focused and unfocused circular ultrasonic transducers operating in the frequency range 0.5 to 10 MHz. The test methods relate to measurements made using both pulse-echo and hydrophone based techniques. The document incorporates technology not present in other international or national standard calibration procedures.

Part 3 - Preparation of Reference Defects and Reference Panels

This draft procedure, based on ISO/DIS 1268 [10], describes the preparation of reference panels fabricated from fibre-reinforced plastic composites with simulated production defects. The panels may be used to adjust the sensitivity and/or resolution of ultrasonic C-scan equipment and to aid with the detection of defects. The procedure can be used with laminates with continuous unidirectional reinforcement and woven fabrics with thermosetting resins.

The draft documents have mainly adopted the definitions and terms in the draft European Standard on Non-Destructive Testing - Terminology - Part 4: Terms used in Ultrasonic Testing (prEN 1330-4). Additional and alternative terminologies to those used in prEN 1330-4 have been used as necessary.

ASSESSMENT OF C-SCAN WORKING DRAFT PROCEDURES

The same panel used in the first R-R exercise has been re-circulated among a number of companies which participated originally. In this second exercise, each participant was required to inspect the panel using the operational procedure developed within the programme. A similar exercise has been carried out to assess the calibration procedure for ultrasonic transducers. Participants were requested where possible to carry out absolute attenuation measurements and to size the defects according to the -6 dB defect sizing method. The majority of the participants were unable to size the defects using the -6 dB method or measure absolute attenuation due to software or hardware limitations. Table 2 shows typical defect size measurements in the X- and Y-directions obtained for double-layered inserts located at the mid-plane of the stepped panel.

Table 2: R-R results for mid-plane defect dimensions using double-through transmission.

Insert width/diameter	**Participant 1**		**Participant 2**		**Participant 3**	
	X	**Y**	**X**	**Y**	**X**	**Y**
Square insert						
25.0 mm	27.3	25.6	27.0	28.5	23.0	25.0
12.7 mm	13.3	13.1	13.0	14.5	11.0	10.0
6.35 mm	6.6	6.8	7.0	8.0	6.0	5.0
Circular insert						
25.0 mm	26.8	26.8	24.0	23.0	25.0	24.0
12.7 mm	13.6	13.6	14.0	14.5	12.0	14.0
6.35 mm	7.3	7.3	6.0	6.0	6.0	7.0

The following observations can be made from the R-R results on the stepped reference panel:

- *All inserts were detected by the participants with the position of the defects being almost identical.*

- *The apparent defect size was similar for all participants that sized the defects using the -6 dB defect method; independent of the size, shape and through-thickness location of the insert.*
- *Differences in apparent defect size was dependent on the inspection technique, inspection parameters, defect type and the software used to determine the -6 dB width. Both circular and square defect sizes were generally overestimated using the double-through transmission method (Table 2) independent of transducer parameters.*
- *The uncertainty in defect size measurement for the single-layer inserts was much smaller compared with the double-layer PTFE inserts with taped edges (i.e. sealed envelope). The reflection coefficient at the taped edges is significantly reduced making it difficult to accurately size the defects using the -6 dB method.*
- *Absolute attenuation measurements varied from 1.2 to 2.0 dBmm^{-1} depending on the inspection technique and the transducer frequency. The measured attenuation coefficient tends to increase with increasing frequency of the inspection transducer. Differences in calibration procedures may also have contributed to variations in absolute attenuation measurements between participants.*
- *Uncertainty in defect size increased with decreasing defect size.*

The uncertainties associated with defect sizing have been reduced as a result of the introduction of the -6 dB defect sizing method, although further effort is required to encourage the wider use of this technique in preference to optical measurements from C-scan images. Further work is required on the -6 dB method to determine the frequency dependence of diffraction at the defect edge and shadowing by the defect. Also, it is necessary to assess the systematic uncertainties associated with the different inspection modes, particularly double-through transmission. The procedures have encouraged operators to adopt a methodical approach to C-scan set-up, inspection and documentation, highlighting all the relevant controlling parameters. The second R-R results show that the relative attenuation measurements between participants are far closer than the previous exercise, where in-house procedures were used.

CONCLUDING REMARKS

Future work concerns the wider adoption of the C-scan procedures by industry through their development as national or international standards. The stepped reference panel will be sent to a number of companies throughout Europe (e.g. DASA) and in the USA (e.g. Boeing/McDonnell Douglas) to be scanned with the NPL draft procedures. The results from the national (Phase 1) and international (Phase 2) validation exercises are to be used to improve the working draft procedures which have been submitted to the British Standards Institution (BSI) for consideration as a new work item (NWI) for CEN (Comité Européen de Normalisation) or ISO (International Standards Organisation) standardisation. These documents are now being processed into CEN frame text versions by the technical committee ACE/56 (Testing of Aerospace Metallic Materials). It is expected that the ACE/64 (Aerospace Structural Reinforced Plastics) committee will provide the necessary composites expertise to assist the review of the documents.

The procedures developed within the programme relate only to flat, monolithic panels made from pre-impregnated sheet fabricated using autoclaves. For the procedures to be widely applicable to realistic structures it will be necessary to accommodate other forms of processing and construction. It is intended to broaden the scope of the procedures to include curved structures, sandwich constructions (foam and honeycomb core) and other processing routes (e.g. resin transfer moulding). Part 3 of the procedure would need to be expanded to cover a wider range of defect types associated with other production routes.

ACKNOWLEDGEMENTS

This work was funded by the United Kingdom Department of Trade and Industry as part of its support of the technological competitiveness of UK industry. The authors would like to express their gratitude to all members of the Industrial Advisory Group (IAG) and to the members of the Project Team, whose contributions and advice have made this work possible.

REFERENCES

1. McDonnell Douglas Process Standard DPS 4.738-2, "Ultrasonic Inspection of Composite Structures", 1988.

2. Boeing Aircraft Company Process Specification Number BAC5980, "Non-Destructive Inspection of Composite Parts and Structures", 1981.

3. ASTM E 1065-96, "Standard Guide for Evaluating Characteristics of Ultrasonic Search Units", ASTM Standards, Volume 03.03, Nondestructive Testing, pp 462-480, 1998.

4. Smith, R.A., "Ultrasonic Defect Sizing in Carbon-Fibre Composites - An initial Study", INSIGHT, Vol 13, No 8, pp 595-605, August 1994.

5. Smith, R.A., Zeqiri, B., Jones, L.D. and Hodnett, M., "Nonlinear Propagation in Water and Hydrophone Methods for Characterising Ultrasonic NDT Transducers", INSIGHT, Vol 40, No 1, pp 12-19, January 1998.

6. Smith, R.A., Jones, L.D., Zeqiri, B and Hodnett, M, "Ultrasonic C-Scan Standardisation for Fibre-Reinforced Polymer Composites - Minimising the Uncertainties in Water and its Effect in Attenuation Measurements", INSIGHT, Vol 40, No 1, pp 34-43, January 1998.

7. Zeqiri, B., Hodnett M., Smith, R.A. and Scudder, K.P., "An Assessment of Pulse-Echo and Hydrophone Methods for Characterising Ultrasonic NDT Transducers", INSIGHT, Vol 40, No 1, pp 20-27, January 1998.

8. Zeqiri, B. and Hodnett, M., "A Systematic Investigation of the Effect of Collimators on the Characteristics of NDT Transducers", INSIGHT, Vol 40, No 1, pp 28-33, January 1998.

9. Smith, R.A, Jones L.D., Willsher, S.J. and Marriott, A.B., "Diffraction and Shadowing Errors in -6 dB Defect Sizing of Delaminations in Composites", INSIGHT, Vol 40, No 1, pp 44-49, January 1998.

10. ISO/DIS 1268 - Part 4, Test Plate Manufacturing Method - Moulding of Preimpregnates (using Autoclave, Pressclave, Hydraulic Press and Vacuum Bag Equipment).