Development of a multifunctional Non-linear acoustic NDI system:

Non-linear Elastic Wave Spectroscopy Imaging

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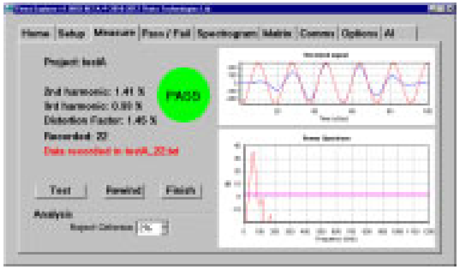
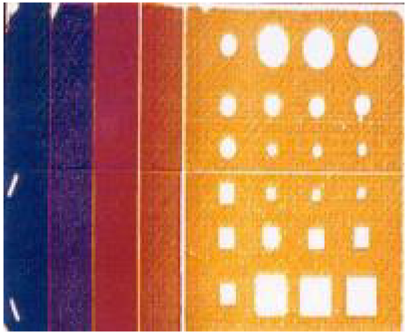
Project Objectives:-

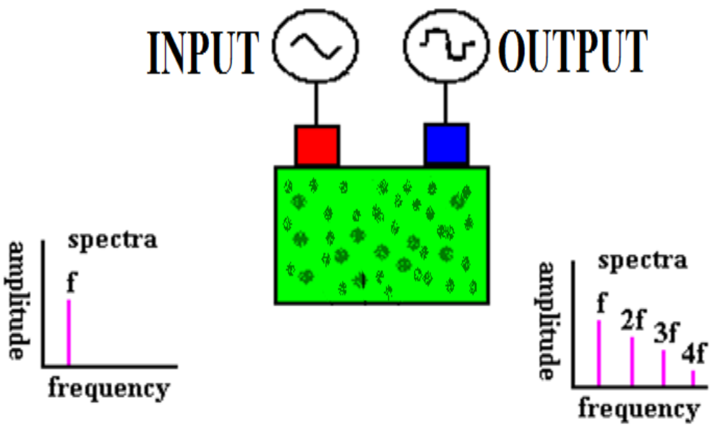
- To review and evaluate the field of imaging of nonlinear wave scattering to be used for NDI in solids or in granular matter and soils.
- To design, build, test and validate a breadboard instrument that is able to image nonlinear scattering sources excited by acoustic waves in a variety of materials.
- To demonstrate and evaluate the feasibility and sensitivity of the concept of imaging nonlinear scattering waves in solids.
- *…..for relevant space applications and materials…and other wider markets as appropriate….*

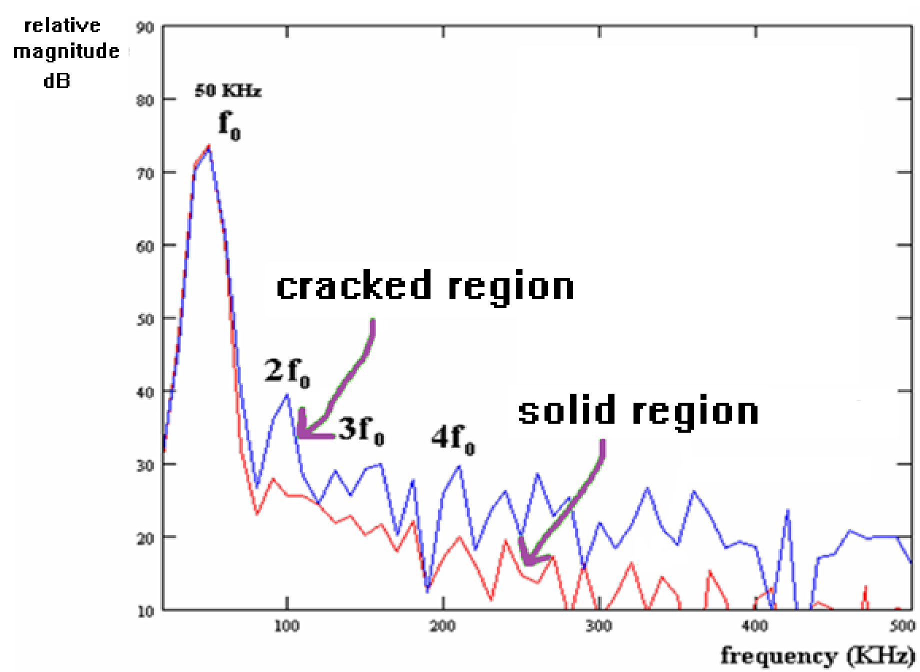




Non-linear acoustics (NEWS) techniques: 1. Single frequency

compressive damage in a concrete cylinder

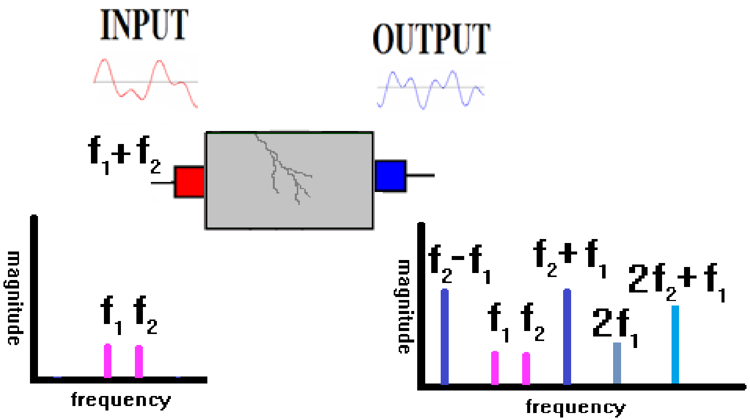


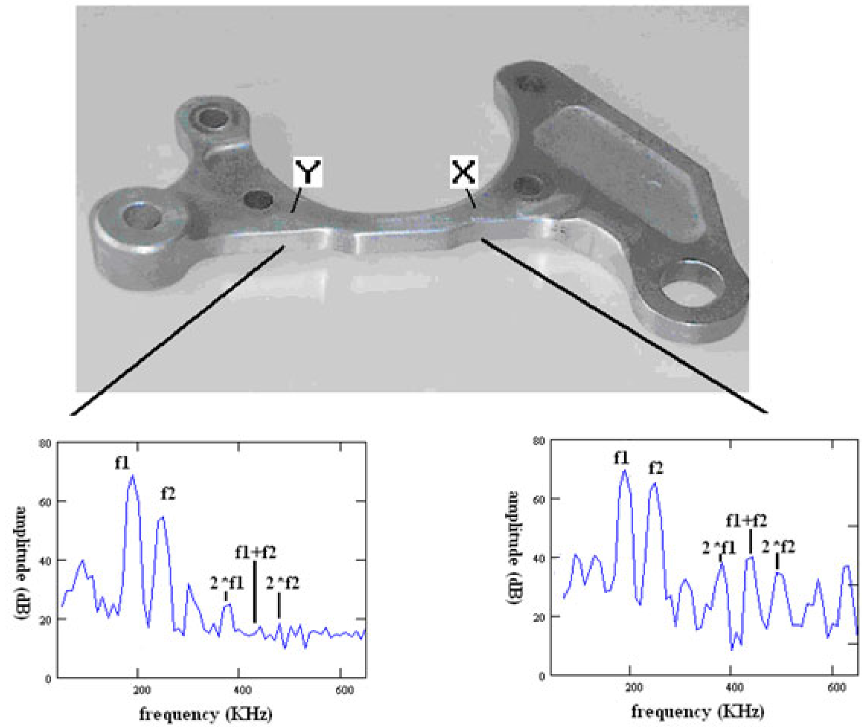


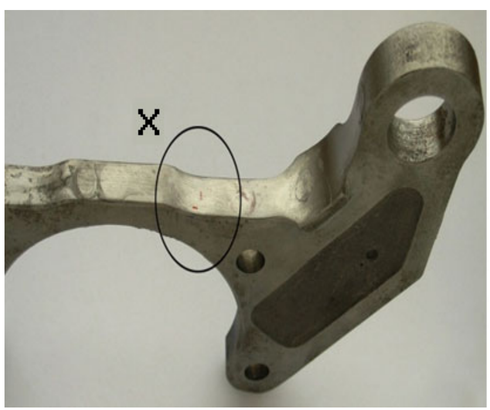
Conventional NDT can detect onset of failure at around 80% of Ultimate Compressive Strength; nonlinear acoustic detection begins around 20% UCS.

Non-linear acoustics (NEWS) techniques: 2. Dual frequency

cyclic stress cracking in a steel steering actuator bracket



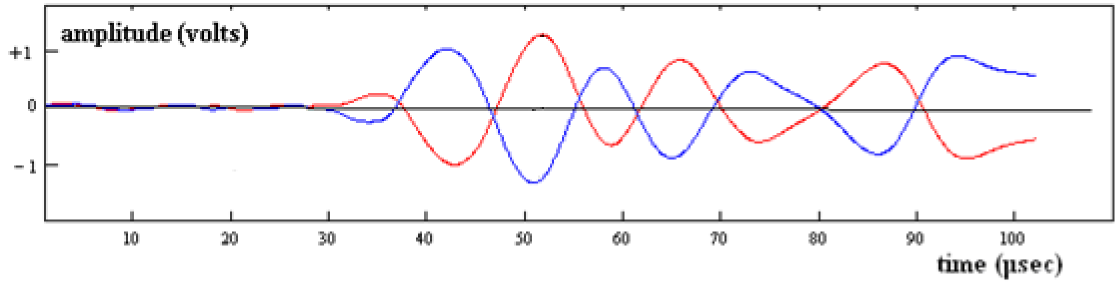




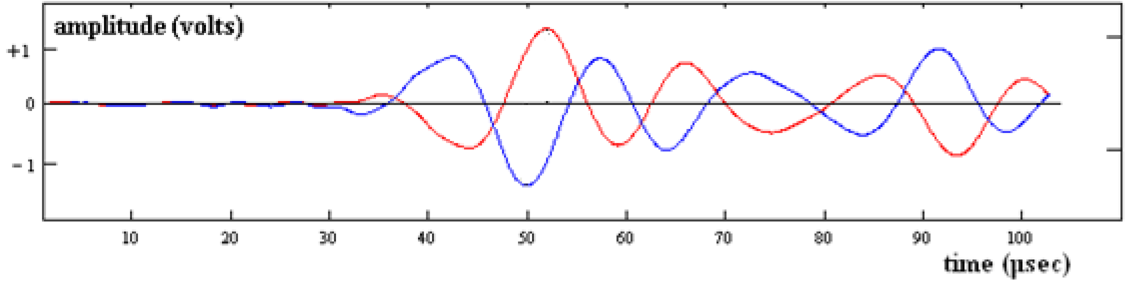
Generation of sidebands and intermodulation products are more sensitive indicators of damage

Non-linear acoustics (NEWS) techniques: 3. Pulse Inversion

tensile loading damage in a thin strip of carbon fibre composite



Compressive and tensile pulses give equal and opposite (symmetrical) impulse responses on linear undamaged materials



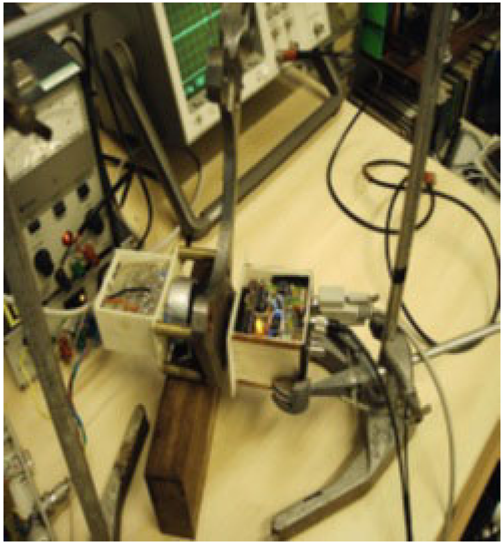
Compressive force closes cracks

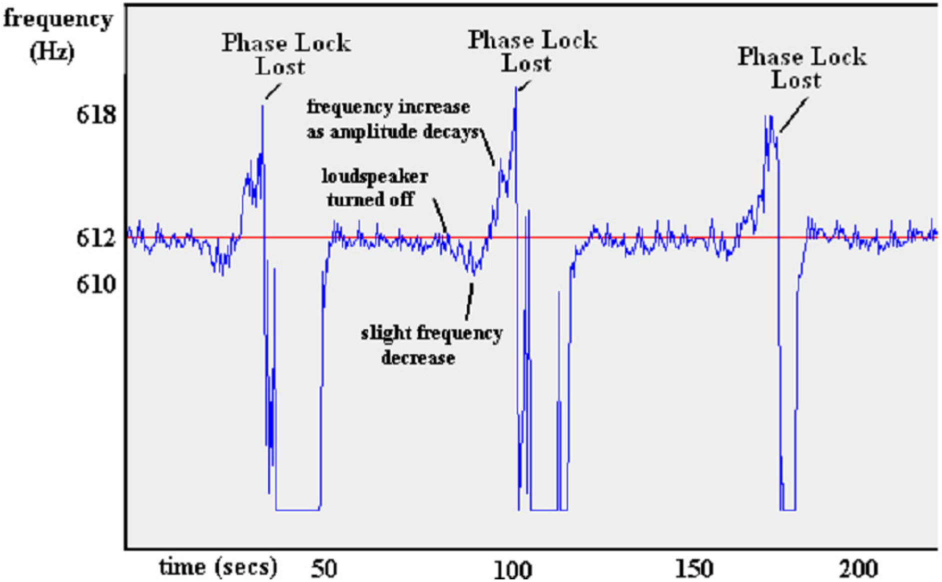
Tensile force opens cracks

Compressive and tensile pulses give unequal impulse responses on nonlinear materials (amplitude and phase differences)

Non-linear acoustics (NEWS) techniques:
4. Resonance frequency deviation ('Resonance Drift')

cyclic stress cracking in a steel steering actuator bracket





Object brought to resonance using a loudspeaker

Frequency very accurately measured as the amplitude decays using a phase lock loop frequency meter

Nonlinear resonance frequency variation versus amplitude

Psi-tran Ltd | THETA TECHNOLOGIES SONIC DEFECT DETECTION | NPL National Physical Laboratory | esa European Space Agency

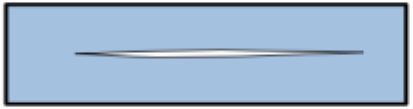
Workshop of leading non-linear acoustics experts (Industry and Academia), 14th March 2013, NPL, London

Conclusions

- Recommendations on candidate reference materials to source/manufacture
  - *Monolithic carbon fibre-reinforced plastic (CFRP) laminates containing: De-laminations; Ply cracking; Impact damage*
  - *CFRP sandwich constructions*
  - *Titanium and/or aluminium alloys :*
  - *Granular materials with transitions from loose and packed structures.*

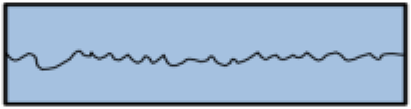
  Kissing de-bond RDAs are important to include – as difficult for conventional NDI to detect
- Limitations of conventional NDI include:-
  - *Inability to detect small defects before they grow to a critical size.*
  - *Inspection of structural parts with complex geometries, i.e. curvatures.*
  - *Necessity to dismantle critical parts for detailed inspections*
  - *Limitations on technique efficiency and reliability for accurate localization and detailed characterization of certain types of damages.*
- NEWS can potentially offer significant advantages over conventional NDI with the ability to diagnose manufacturing defects such as incipient damage in CFRPs and metals and alloys in the form of:-
  - microcracks
  - delaminations
  - clapping areas /adhesive bond weakening/ kissing de-bonds
- Recommendations on NEWS methods to investigate for further development:-
  - *Dual frequency*
  - *Pulse inversion*
  - *Resonance drift*
  - *Non-linear Air Coupled Emissions (NACE) alternative to contact c-scan imaging.*

Delamination



Separation between FRP plies, zero strength

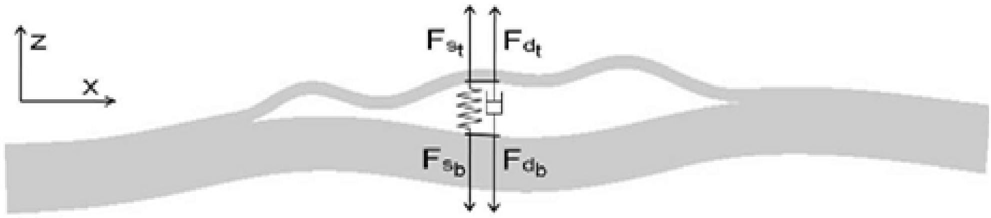
Kissing de-bond



Mechanical/frictional contact without a chemical bond

Numerical modelling

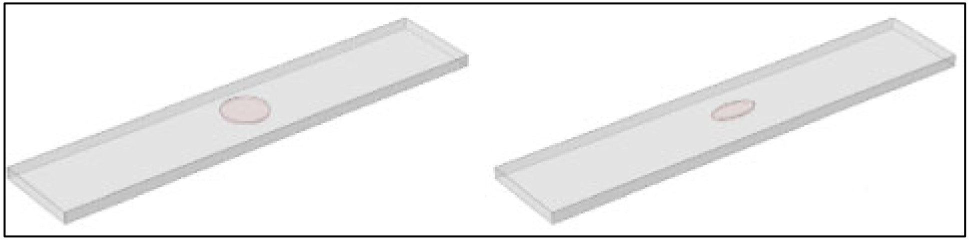
- Comsol Multiphysics + Contact Acoustic Nonlinearity



- In house developed 3D FDTD model accounting for
  - Reversible Stress-Strain nonlinearity (extension of Hooke's law)
  - Hysteretic Stress-Strain nonlinearity (Preisach space)

- Guidance and optimisation of techniques

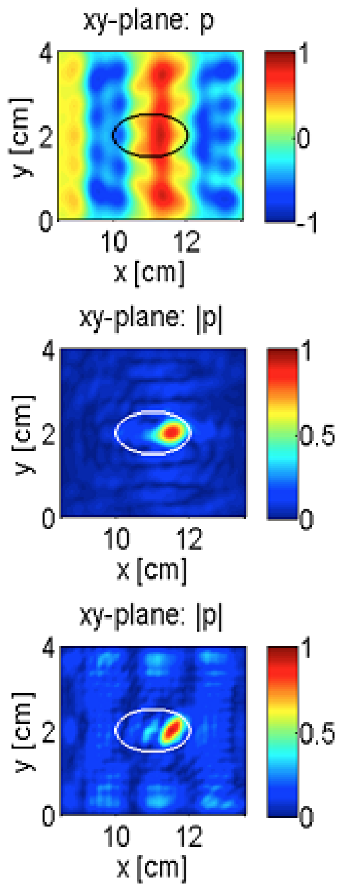
KU LEUVEN kulak



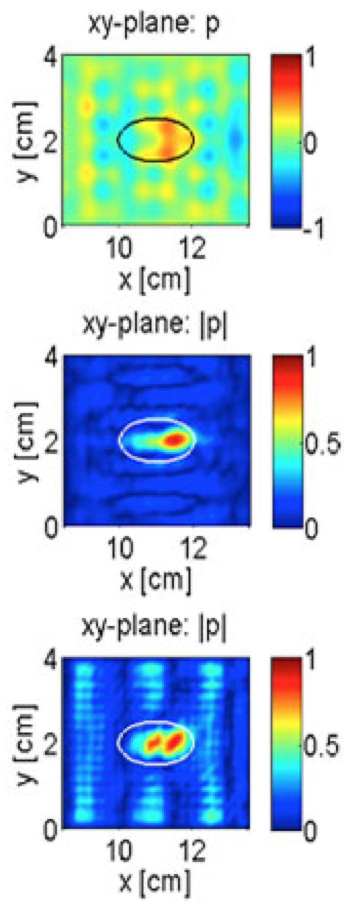
- Kissing de-bond simulation
- CFRP example properties

Numerical modelling

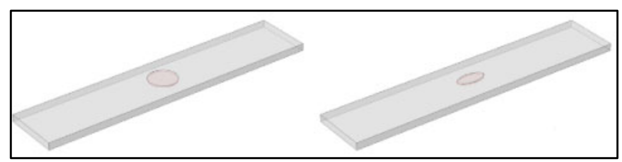
Infinite Plate



Finite Plate



Reflecting boundary (non-infinite specimen): Increase in noise due to reflections, but still able to detect defect at 5-15mm above surface



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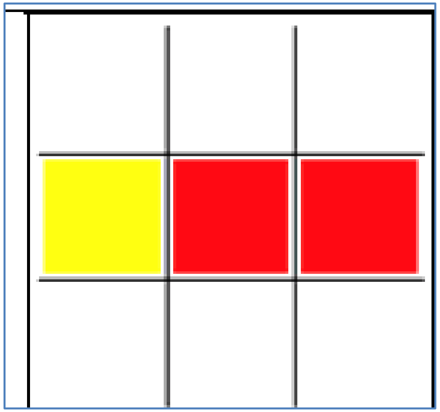
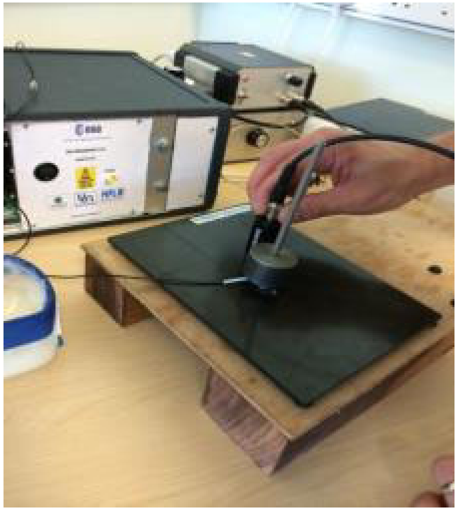
Build and test of NEWSI system

- Build system and Develop basic software function for data acquisition and analysis
- Functionally test all sub-systems
- Software for imaging has focussed on single frequency defect discrimination to understand performance of basic operation mode.
- Display colours represent ‘threshold – sigma confidence levels’ of the harmonic ‘signature’ of a control sample of the undamaged materials compared to the defective RDA sample.
- White and yellow are no-detection, orange is threshold level of detection of a defect and red is high confidence (3 sigma) detection of a defect.



3x3 scan of composite RDA with kissing de-bond



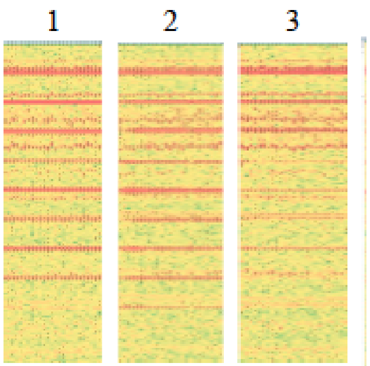
Non-linear Air Coupled Emissions (NACE)

- NACE – scan of air-coupled detection of kissing de-bond RDA
- Spectrograms indicate a change in harmonic signature
- The top spectrogram shows the fundamental and lower down various harmonics with the receiver positioned over the defect (1 and 2) and a different location away from the defect (3).
- In a control sample (bottom image), the harmonic generation is noticeably weaker compared to the defect area.
- Analyser discrimination software not yet optimised for NACE

2.2. Results

Defect

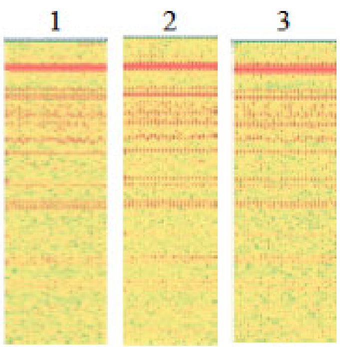
Spectrograms



	1	2	3
Signal Range	216	337	148
Horizontal	3.45	3.45	0
Vertical	2.6	2.6	2.6
Time	12:39	14:43	14:48

Control

Spectrograms



	1	2	3
Signal Strength	264	249	412
Horizontal	0.5	0.5	-0.09
Vertical	2.45	2.79	2.79
Time	11:27	11:33	11:36

Figure 7 - Control Results

Reference Defect Artefacts

- NPL manufactured:-
  - RDA7 transverse Ply-crack (strain) CFRP
  - RDA8 BVID – impact damage 1 - 20J BVIDs
  - RDA9 Kissing de-bond with range of defect sizes – 50mm to 5 mm

- Available RDA's were tested with the following complementary methods
  - SAM with depth profiling
  - Microwave
  - X-ray
  - Pulse thermography
  - Visual inspection/microscopy

- No surprises – the conventional NDE detected the defects where they were expected to
- Best method for detecting defects in CFRP was the SAM
- No conventional NDE methods could detect the kissing de-bonds in RDA9
- SAM was able to see the manufacturing defect voids, stress cracks and BVID damage in RDA7,8,9

Table 3: NDI techniques used for comparative inspections of RDAs

RDA detail		NDI technique						
Nº	Name	SAM			Microwave	X-ray	Pulse thermography	Visual/ microscopy
		5 MHz*	15 MHz	75 MHz				
1	CFRP C-scan reference panel	✓	✓		✓	✓	✓	X
2	Ti6Al4V TIG welded panels		✓		X	✓	✓	✓
3	Insert sandwich construction	NOT AVAILABLE FOR INSPECTIONS						
4	Granular material sample							
5	Metallic kissing de-bonds							
6	Metallic samples containing fatigue cracks		✓		X	✓	✓	✓
7	CFRP transverse ply cracking			✓	✓	✓	✓	✓
8	CFRP impact damage	✓	✓		✓	✓	✓	✓
9	CFRP kissing de-bonds	✓	✓		✓	✓	✓	X
10	Residual stress		X		X	X	✓	X
11	CFRP very low energy impact damage		✓		X	X	X	✓

* - 5 MHz ultrasonic C-scan transducer

SAM Image of RDA 9

- 50mm KDB defect (in centre of panel RDA 9)
- Control panel with nominally zero defects
- The SAM images show that the RDA 9 was manufactured with unintentional voids due to air inclusion in adhesive.
- However, no conventional NDI methods could see any signs of the KDB defects
- Delamination of a trial KB9 shows the defects are present:

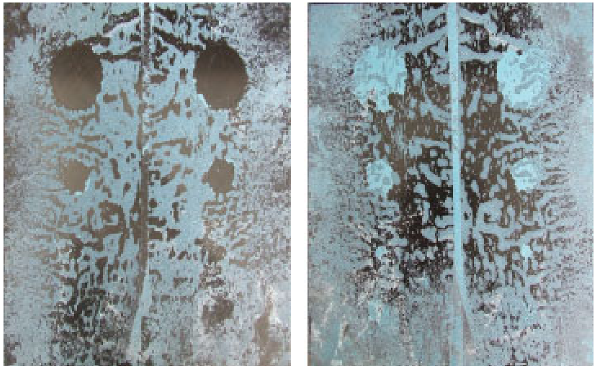


Figure C25: FHS001 (control)

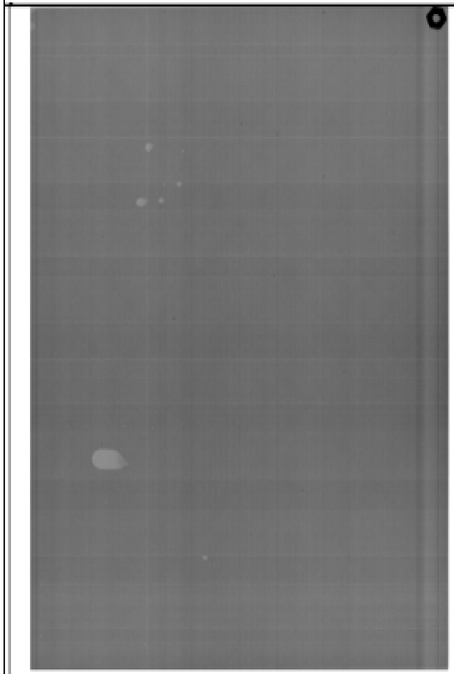
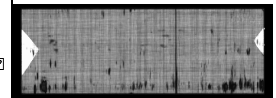
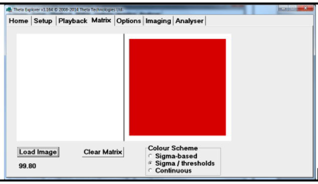
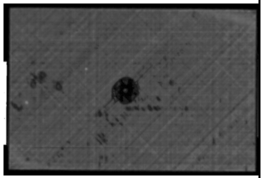
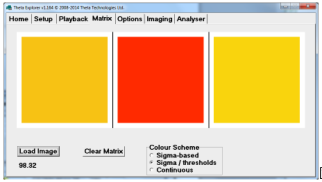
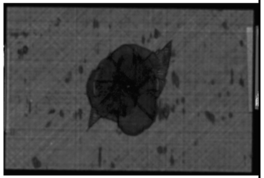
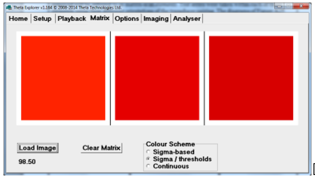
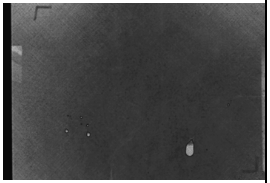
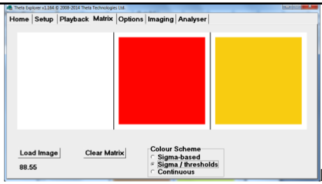
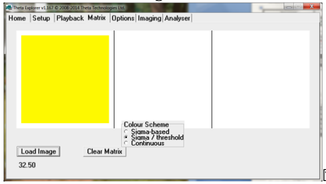


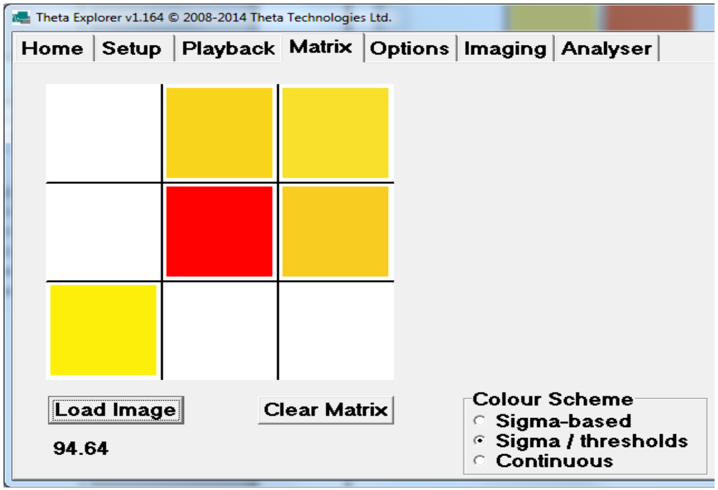
Figure C28: FHS004 (50 mm diameter)

NEWSI test results

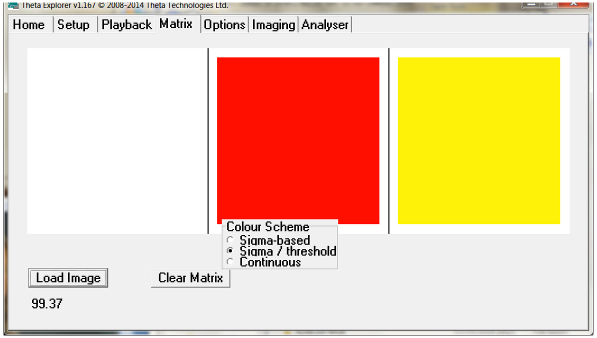
- Summary of results of NEWSI tests on CFRP ply-crack, 5J & 20J BVID, and 50mm KDB RDAs
- NEWSI 3 x 1 scans across a diagonal though 50mm KB area
- Comparison of NEWSI and SAM highlights benefits of NEWSI
- SAM does not detect KDB, but detects the ply-crack, impact at 5J and above
- NEWSI shows good evidence of detecting the KB defect
- NEWSI also appears to detect at low threshold edge effects and or manufacturing defect voids seen in SAM tests. (Note edge effects in modelling results).

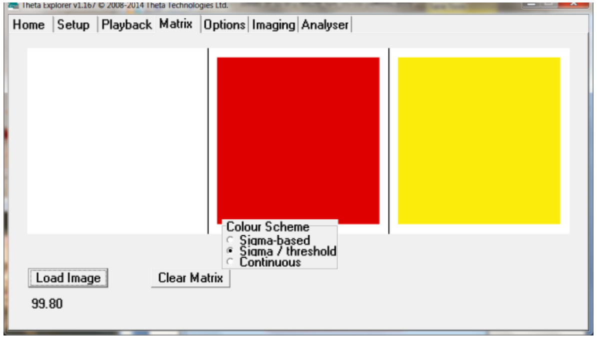
RDA detail		Best NDE technique:		Best NEWSI technique:	
N°.	Name	Name	Result		Result
7	CFRP transverse ply cracking (1 ply crack)	SAM (75 MHz)			
8	CFRP impact damage (5J)	SAM (15 MHz)			
	CFRP impact damage (20J)	SAM (15 MHz)			
9	CFRP kissing de-bond (50mm)	SAM (15 MHz)			 50mm kissing de-bond scan  Control scan

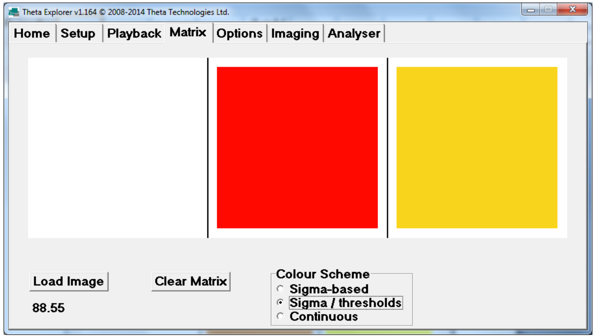
Kissing de-bond Tests



Only Central response above detection threshold







- Repeated tests on 50mm KBs
- Diagonal 3x1 scans
- Consistent central detection (white and yellow is below detection threshold.)

Conclusions

- The main objective of designing, developing, demonstrating a breadboard instrument to detect defects that are challenging areas for conventional NDE has been achieved with single frequency and early NACE mode operation

- Power levels needed for NEWSI are at state of the art in terms of amplifier and transducer TRL – more work on both is needed to improve reliability and signal levels launched within RDAs

- The system is capable of further development to implement detection algorithms for all the operating modes.

- The test time needs to be speeded up and improved NACE receivers and better wave propagation into specimens will improve testing speed.

Further Work

- Algorithm development for dual frequency and pulse inversion
- NACE transducer development
- Contact refinement (transducers and coupling)
- Automated scanning – hardware development
- Improved CFRP kissing debond RDAs
- Improvements to power amplification
- Faster software processes – real-time scanning and detection feedback
- Resonance drift RDAs – metal artefacts, complex geometries, defective and intact