HEALTH MONITORING OF AIRCRAFT BY NONLINEAR ELASTIC WAVE SPECTROSCOPY

AERONEWS

EC SIXTH FRAMEWORK PROGRAMME
PRIORITY 4: AERONAUTICS AND SPACE
SPECIFIC TARGETED RESEARCH: AST3-CT-2003-502927
PROJECT WEBPAGE: http://www.kuleuven-kortrijk.be/aeronews/
PROJECT COORDINATOR: Prof. KOEN VAN DEN ABEELE

Deliverable D5 and Milestone M2

Feedback of the observations toward the technological development of a test device inspection system, and decision on the NEWS techniques to be implemented on the full-scale validation model.

Period covered: from March 1, 2004 to February 29, 2008

Date of preparation: October 15, 2007
Update: April 15, 2008

Start date of project: March 1, 2004 Duration: 4 years (February 29, 2008)

Project coordinator name: Koen Van Den Abeele
Project coordinator organization name: KULeuven
Report author: Charles Courtney (UNIVBRIS), Sigrun Hirsekorn (IZFP)

Final version (confidential)

Table of contents

1. Overview of the tasks, deliverables, and milestones of WP1

WP1: Optimisation of NEWS techniques to detect micro-scale damage in aircraft components and structures

Workpackage leaders: Fraunhofer Institute for Nondestructive Testing, Germany (IZFP)
University of Bristol, UK (UNIVBRIS)
Partners: KULeuven, VUB, ASCO, ITASCR, VZLU, GIP-U, NDTE, UNI-Na, CSIC, BR&TE, BODYCOTE, CU

The overall objectives of WP1 are:

- Extend and prove the use of NEWS methods on various materials and structures in aeronautics with focus on detecting resident delaminations and weak bonds in composites, microcracks in alloy parts, and on the assessment of early stage damage due to external loading.
- Determine and define methodological approaches and limitations of the NEWS techniques applied to different materials, parts, and structures.
- Prove the efficiency and the advantages of NEWS compared to traditional NDT methods for monitoring and imaging microscale induced damage and fatigue of airframe parts.
- Supply feedback in terms of resolution and experimental demands of NEWS techniques for different types of tested objects.

To enable these objectives to be achieved sub-tasks, deliverables, and milestones were defined.

Sub-tasks and Milestones:
WP1.1: Identification of critical parts and structures and driving failure scenarios of interest to aeronautics NDT (months 0-6),
Milestone 1: List of critical parts and failure scenarios to be considered (month 6),
WP1.2: Testing of single parts: composites, layered media, metallic parts (months 0-24 (42)),
WP1.3: Testing of complex structures (months 6-36 (48)),
WP1.4: Formulation of feedback and supply of guidance for the implementation of particular NEWS methods (months 18-36),
Milestone 2: Decision on the experimental NEWS methods to be implemented in the full-scale validation model (month 36).

Deliverables and Milestones:
D1: Identify critical parts and structures of interest to aeronautics NDT (delivery dates at months 3 and 6, milestone 1 at month 6),
D2: Identification of most common failure scenarios (delivery dates at months 6 and 12),
D3: Description and critical evaluation of the methodology and results from application of NEWS for quality control of composites, layered materials and metals and their comparison with competing methods (delivery dates at months 12, 18, 24, 30, 36, and 42),
D4: Feasibility test of several NEWS techniques on thin extended structures, complex geometries and rotating parts (delivery dates at months 18, 24, 30, 36, 42, and 48),
D5: Feedback of the observations toward the technological development of a prototype inspection system (delivery date at month 36, milestone 2 at month 36).

Deliverables 1 and 2 were completed at month 12, comprising milestone 1 at month 6. Major activity in deliverable 3 was completed in month 30, with only minor activity continuing. Deliverable 4 reported at month 36 and has only minor activity continuing.

2. Overview of Deliverable 5 (D5) and its sub-deliverables

D5 “Feedback of the observations toward the technological development of a test device inspection system.” Is divided into two sub-deliverables:

D5_1 Quantify the limitations of the various NEWS techniques
Partners: IZFP, KULeuven, ITASCR, NDTE, UNI-Na
Delivery Date: month 36.

D5_2 Assess the feasibility of test device development of the NEWS techniques
Partners: VZLU, GIP-U, NDTE, CSIC, BR&TE
Delivery Date: month 36

Deliverable 5 leads **milestone 2** (at month 36) in the form of a decision on the experimental NEWS techniques to be implemented on the full-scale validation model.

D5_1 requires the quantification of the limitations of the various NEWS techniques. A great deal of work has been undertaken in WP1 to develop and characterize these techniques. Table 3.1 summarizes the techniques and the research groups responsible for their implementation. The techniques are divided into two broad categories: global techniques, which probe an entire component and detect damage without localization, and local techniques which can identify the position of damage either by imaging the whole component from a set of measurements, or by testing a small area for damage and covering larger components by scanning. Tables 3.2 and 3.3 summarize the results of testing with local and with global techniques, respectively, for each type of damage considered. A variety of samples were chosen (including aluminium wing panels, steel steering actuator brackets and composite panels) to cover the damage types and component geometries of interest (identified in section 7.6 of the project’s description of work). The varied nature of the components meant that no single technique is applicable across the board; various techniques need to be applied to cover the range of materials, geometries, and damage types of interest in aeronautical engineering.

Four principal types of component, of interest in aeronautical engineering have been identified and considered: thin metal extended structures, volumetric metal structures, composite panels, and adhesive joints. Thin metal extended structures such as wing panels prove difficult to apply NEWS techniques due to the difficulty in exciting them with sufficient amplitude (see section 5.1 of the Deliverable 4 month 36 report [WP1-D4 report]). This is a particular problem for global techniques, such as ultrasonic inter-modulation using continuous excitation, which rely on exciting the whole structure above a critical level. Composite parts have the additional difficulty of high attenuation. Complex geometry metal parts are more straightforward, but still present access and excitation difficulties. Adhesive joints have the advantage of relatively well localized and aligned potential damage sites.

3. Limitations and applications of techniques

Table 3.1: NEWS Techniques.

Technique	**Groups**	**Global/ Local**	**Experimental Practicalities**
Nonlinear UT Transmission	IZFP	L	$LiNbO_3$ and PMN-PT 2MHz Driving Transducers. 5MHz-centre-frequency broadband receiver. RITEC System
UT Inter-modulation	UnivBris ITASCR CU	G (L)	2 or 3 2-mm-thick 5-mm-diameter piezoceramic disks. 1 or 2 Power amplifiers (eg Amplifier Research 75A250). OR 7 transducers, two signal generators, two amplifiers and a multiplexer for localization tests
Resonant frequency analysis (RFA)	KUL CSIC	G	Piezoceramic transducer or loudspeaker. Laser Vibrometer or accelerometer.
Nonlinear Time Reversal Acoustics (TRA)	KUL GIPU ITASCR	L	See body of text
Frequency response function (FRF)	UniNa	G	Piezoelectric patch Laser Vibrometer
High Frequency Multi sine	VUB	L	2 surface-wave transducers with wedges. (Tests performed during fatigue process)
Phase Coded Pulse Sequence	BODYCOTE	L	Immersion scanner. 5MHz-centre-frequency broadband transducer. Power Amplifier
Impact Modulation	KUL	G	2 Dakel IDK09 transducers. Power Amplifier Hammer
Contact Phase Modulation	GIPU	L	Low Frequency Transducer

Local Techniques

Local techniques, which attempt to identify the position of the damage not just its presence, were assessed using an array of samples. These results are summarized in table 3.2 and discussed in more detail below.

Table 3.2: Local techniques applied to each damage type.

Damage Types	**Samples**	**Technique**	**Example Result**
Fatigue Crack	Bracket	Nonlinear UT Transmission	No damage detected
		TRA	9-mm crack located
	ASCO Cracked Sample	TRA	10-mm crack located
	VZLU Sample	TRA	Damage detected
	Wing Panel	TRA	2-mm crack located
		High Freq. Multi-sine	Crack growth monitored
		Phase Coded Pulse Sequence	No damage detected
	Al Boeing Samples	TRA	Ongoing
Delamination (Impact, thermal load, bending load)	Composite Panel	Nonlinear UT Transmission	Pre-delamination damage imaged
Incomplete / Weak Bonding	Adhesive Joints	Nonlinear UT Transmission, Phase Coded Pulse Sequence	Variations in bond strength measured
Rivet Crack	NDTE Composite Sample	TRA	Poor
Laser Induced Cracks	PMMA	TRA	Damage located
Cracked Glass	Bi Layers	Contact Phase Modulation	Poor detection of non-linearity in bi-layers

Nonlinear Time Reversal Acoustics

Using local methods that focus energy into a small region of a larger sample overcomes the difficulty in exciting large thin-extended samples. The TR-NEWS approach (one of the two time reversal acoustics approaches outlined in section 3.4 of the D3 month 30 intermediate report [WP1-D3 report]) uses linear time-reversal acoustics to focus energy at a point; the nonlinear behaviour at that point then being measured using a technique such as inter-modulation. This approach proved effective in imaging the crack grown in a model wing panel (see section 3.4 of the WP1-D3 report and section 5.5 of the WP1-D4 report). The steering actuator bracket was an example of a complex three-dimensional component and had low attenuation making it particularly suited to nonlinear TRA which successfully imaged a 9-mm crack in the sample. This application required the use of three transducers for excitation and a laser vibrometer, in general the experimental requirements both in terms of excitation and detection (requiring multiple well-coordinated receivers/sources and some form of scanned receiver), and signal handling (particularly for NEWS-TR methods where a reverse model is required) are arduous for the TRA techniques tested. The application of the technique to the wing panel is also time consuming, taking up to a day to scan a small region of the sample restricting its feasibility at this point, however a multiplexed system has been operated taking only a few minutes to test, with some success.

High-frequency multi-sine

High-frequency multi-sine measurements (described in section 3.5 of the WP1-D3 report) can be used to detect cracks during the fatiguing process and proved effective on the wing panel and on slat tracks. Unlike other techniques tested, this approach is applied during fatiguing and relies on the fatiguing force to provide the low frequency oscillation. This means that damage can be detected in real time during operation. The technique was successful in detecting and following the growth of the crack in the wing panel from 0 to 17.1 mm.

Nonlinear UT transmission And Phase-Coded Pulse-Sequence Technique

Where defect localization is known (or if there is a particular hot-spot that is of interest) local techniques, such as nonlinear UT transmission, can be particularly effective. For example the bonding in adhesive joints is of interest, the known orientation of the interface leads to transmission techniques such as the phase-coded pulse-sequence technique (see section 3.9 of the WP1-D3 report) and nonlinear UT transmission (see section 3.1 of the WP1-D3 report) both of which successfully detected weak bonding. Ultrasonic transmission measurements offer the possibility of rapidly (each test takes a few seconds) determining adhesive bond strength between aluminum substrates up to 25 MPa with the used equipment and transducers.

Impact damage to composites leads to delamination parallel to the panel surface and so was suitable for application of nonlinear UT transmission, which detected and imaged such damage (see section 3.9 of the WP1-D3 report). This technique is particularly suited to detecting pre-delamination microcrack fields before complete delamination (which can be detected more easily by linear methods). UT transmission was unable to detect the crack in the steering actuator bracket due to the component geometry preventing appropriate excitation.

Global Techniques

Global techniques for testing components rely on exciting the entire sample in order to detect the presence, but not the location of damage. Volumetric components with low attenuation are most straightforward for most of the global techniques; in particular those using inter-modulation of two excitations such as UT inter-modulation and impact inter-modulation (see sections 5.4 and 5.6 of the WP1-D4 report). The complexity of the geometry does not present a major obstacle provided that the sample can be excited successfully and measurements are quick with straightforward experimental set-ups.

Table 3.3: Global Techniques applied to each damage type.

Damage Types	Samples	Technique	Example Results
Fatigue Crack	Steel Sections	UT Inter-modulation	5-mm crack detected
	Wing Panel	UT Inter-modulation	Large (18mm) crack detected
	Bracket	UT Inter-modulation RFA Impact Modulation	9-mm crack detected 9-mm crack detected 9-mm crack detected
	Clevis Att.	UT Inter-modulation	Possible micro damage detected. Inconclusive
	Al Boeing Samples	RFA	Failed to detect 1mm crack
	Al Fuselage Patch	FRF	3-mm crack detcected and located
	Landing gear fork leg	UT Inter-modulation	Crack detected
Laser Induced Cracks	PMMA	UT Inter-modulation	Cracks detected
Impact Damage /Delamination	Composite Panel	UT Inter-modulation FRF	Good 6-mm delamination located in panel
Thermal Damage	Composite Panel	RFA	Increase in nonlinearity correlated to temperature and exposure time
	Glass	RFA	Distributed cracks detected

Rivet Faults	Al Panel	FRF	Missing rivet in stringer detected
Chemical Corrosion	Boeing Samples (Duraluminium)	RFA	Distributed corrosion damage detected

Resonant Frequency Analysis

Nonlinear reverberation spectroscopy and resonant frequency spectroscopy were used in order to analyze variations in the resonant vibrations in amplitude. Both met with some success (see section 3.8 of the WP1-D3 report and 5.3 of the WP1-D4 report), particularly in detecting the crack in the steering actuator bracket. Nonlinear reverberation spectroscopy, looking at the variation of resonant frequency with declining amplitude, detected the 9-mm crack in the steering actuator bracket with a factor of three increase in amplitude-frequency gradient between undamaged and damaged samples. The test took approximately one minute. Distributed damage (due to thermal treatment) in composite material resulted in up to a ten times increase. There are some limitations (free support desirable, low attenuation materials), but this approach is relatively quick (approximately one minute to test).

Resonant frequency analysis at varied driving amplitude gave similar results to non-linear reverberation tests on cracked metal samples. The tests were undertaken on duraluminium samples supplied by VZLU and comparison between a 3mm crack and a 6.5mm crack lead to a doubling of the non-linearity measurement. This approach was also successfully applied to distributed damage in the form of chemically corroded aluminum and thermally cracked glass. With increases of the order of 1.5-2 in the measured parameter. This approach was more time consuming than non-linear reverberation taking several minutes to perform.

Ultrasonic inter-modulation

Ultrasonic inter-modulation (where the mixing of two ultrasound frequencies due to nonlinearity in the sample is measured) also showed similar success with the steering actuator bracket, although it was more time consuming (see section 3.2 of the WP1-D3 and 5.6 of the WP1-D4 report). Initial tests using single modes were quick, taking a few minutes to perform and detected cracks as small as 5mm (8% cross-section) in steel samples, however these were found to be strongly dependent on the frequencies used for excitation. A more robust technique using multiple pairs of excitation frequencies was developed and used to detect the 9-mm thumbnail crack in the steering actuator bracket. This approach ensured better coverage of the sample, but took longer (30 minutes) to perform. Although generally tested for global detection use of a multiple (7) transducer multiplexed system allowed detection of and approximate localization of a fatigue crack in a landing gear fork leg.

Impact Modulation

Impact modulation used an impact with a hammer to produce low frequency (<20kHz) excitation of a sample which modulated a high (~400kHz) frequency signal (see section

5.4 of the WP1-D4 report for a fuller explanation and results). The decay with time of the low frequency vibration allowed the sideband signal (due to non-linearity) to be measured as a function of low-frequency amplitude. For tests on the steering actuator bracket this lea to a 3 to 10 times increase in the measured value between the undamaged and damaged samples. The test took a minute, but required the sample to be hung so it could resonate freely and required some care to ensure consistency of the impact.

Frequency Response Functions

Global techniques are more problematic in high attenuation components and extended structures due to the difficulty in delivering excitation energy to the entire component. One method that has proved effective for global inspection of thin extended structures is the analysis of frequency response functions. Frequency response functions for components with and without damage have been used to inspect plate-like structures (including real aircraft fuselage panels) successfully (see section 3.7 of the WP1-D3 report and 5.7 of the WP1-D4 report). The differences were successfully identified using both a damage index (based on the average difference between FRFs over a frequency range) and neural networks trained using undamaged FRFs. The technique can also be used with multiple transducer patches to provide localization of the damage position and took a few minutes using 20 grid points.

4. Milestone 2

The need for multiple techniques to cover the variety of components found in a typical aerospace application is clear. Table 4.1 summarizes the areas of interest and the techniques that will be taken forward to the validation stages. They were chosen based on the ability to detect damage and a consideration of the practical feasibility. Most of the techniques were practically relying on existing technologies (such as ultrasonic transducers and accelerometers) for their application, which just require optimising, improving and integrating with custom electronics for non-linear tests, and should lend themselves to further development. The time taken for the time-reversal acoustics tests presents a challenge to its practical development, but the ability to accurately image damage in the most difficult samples suggests that these are worth addressing.

The selection of time reversal acoustic, high frequency multi-sine, frequency response function, resonant frequency analysis, inter-modulation and nonlinear UT transmission techniques ensures that for each component type both a global and local technique is being developed, with the exception of adhesive joints where small regions (the joints) are to be inspected, removing the need for a global approach, and ensures that development towards demonstration continues on all the successful feasible methods.

Table 4.1: Summary of decision made for Milestone 2

Component Type	**Techniques**
Extended Thin Metal	TRA (Local) High Frequency Multi-Sine (Local) FRF (Global/Local) RFA (Global)
Volumetric Complex-Geometry Metal	TRA (Local) High Frequency Multi-Sine (Local) Inter-modulation (Global) RFA (Global)
Composite Panels	Nonlinear UT Transmission (Local) FRF (Global/Local)
Adhesive Joints	Nonlinear UT Transmission (Local)

5. Summary and Conclusions

Deliverable 5 and the associated milestone 2 represent an assessment of the limitations and feasibility of the various approaches considered during WP1. To this end the approaches taken have been summarized along with the components to which they have been applied and the degree of success. The techniques were divided in to two categories (local and global) and applied to a large variety of sample types (broadly divided in to extended thin metal, volumetric complex geometry metal, composite panels and adhesive joints) of interest to the aeronautics industry. The success of each technique in detecting damage in each sample was evaluated, as required by sub-deliverable **D5_1**, and their practical feasibility assessed, completing sub-deliverable **D5_2**, as a result it was clear that no one technique has been successful for all component types and defects. As a consequence, **milestone 2** constitutes a decision on a suitable selection of techniques to cover the component and defect types of interest (summarized in table 4.1). Global and local techniques were sought for each component type and the success in detecting damage and feasibility of further development of the technique considered in the decision.