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/
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Milestone M3

Simulation study of the feasibility to apply defects localization and imaging methodology based on NEWS techniques

FINAL REPORT (48M)

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

Date of preparation: April 15, 2008

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

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Final version (confidential)

1. Introduction

Milestone M3 is a critical evaluation of the feasibility of NEWS-based damage imaging methods applied to structural aircraft components. It summarises the main conclusions drawn from the extensive numerical modelling performed as part of the sub-package *WP2.2: Damage localization procedure and NEWIMAGE*.

Work Package 2 has devised, tested and analysed – via analytical and numerical modelling – a range of NEWS-based damage detection methods. Results have shown that these methods can offer advantages over traditional techniques, especially with regards to sensitivity during early stages of damage.

This report focuses on the development of NEWS-based localisation and imaging methods. What follows is a summary of the most relevant outcomes from WP2 regarding damage localisation, with reference to Deliverables D6, D7, D8, D9 and D10 in their final version (month 48).

2. Numerical models

In order to simulate the acoustic/ultrasonic interrogation of structures, it was necessary to develop material models capable of describing the nonclassical nonlinear behaviour of damaged materials. This behaviour is linked to the material possessing a large concentration of discontinuities (such as micro-cracks) at the meso-scale. The complex interactions between these features and the elastic material surrounding them are responsible for the non-unique, hysteretic mechanical behaviour verified experimentally (see Deliverable D6).

Furthermore, it was necessary to incorporate the novel material formulations into models capable of simulating nonlinear wave propagation in larger domains, both 2D and 3D. For that purpose, different numerical schemes were utilised including finite difference and finite element methods. WP2 partners were able to develop different approaches according to their own expertise. Common ‘benchmark’ cases were then analysed using the different models in order to verify consistency and validity. Agreements were observed in a round of common virtual experiments; see Activity Report (6m) for details.

Finally, the different approaches available for modelling NEWS techniques were:

- POLITO: Interstitial spring model implemented in the LISA (Local Interaction Simulation Approach) software. Their approach is based on the concept of interstices being present between grains of solid material. These interstices generate non-unique (hysteretic) boundary conditions, and their behaviour is either rigid or elastic depending on local pressure. For each interstice, an ensemble of hysteretic units is considered under a modified PM-space formalism. A custom finite difference scheme (LISA) is then used to solve over the domain.
- KULeuven: Multiscale hysteresis model implemented in the EFIT (Elastodynamic Finite Integration Technique) code. KULeuven’s multiscale model combines a PM-space of bistable hysteretic units with classical nonlinear elasticity. For multidimensional analyses, the stress tensor is decomposed into its eigenstresses and a scalar PM-space is associated with each eigenstress.

- GIP-U: Variations of the PM-space hysteresis model implemented in a pseudo spectral time-domain algorithm. For their hysteretic elementary units, GIP-U considered the models developed by KULeuven and POLITO. Multidimensionality was also handled via eigenstress decomposition.
- CU: Multiscale hysteresis model implemented in DYNA3D (an explicit-integration finite element code). A variation of the PM-space model is used to represent hysteresis and classical nonlinearity is introduced at a macroscopic level. The implementation for 3D solid elements assumes material isotropy, therefore the PM-space is controlled by volumetric strain.

3. NEWS-based imaging methods

From the beginning of the project a number of methods have been considered as potential options for NEWIMAGE, which is the name given to one- two- and three-dimensional damage localisation and imaging techniques based on NEWS.

After early feasibility studies, few methods were chosen for further investigation and development. From these, two options emerged as the most promising techniques:

- MuMoNRAS: multi-mode nonlinear acoustic resonance spectroscopy. It is based on the analysis of resonance frequency shifts for the various modes of an object. It has been developed and applied to one-dimensional problems, but it was demonstrated that the method can be extended to higher dimensions as well.
- NL-TRA: nonlinear time-reversal acoustics methods. It comprises a number of techniques which combine NEWS methods with time-reversal acoustics principles. NL-TRA techniques have been extensively investigated in this project.

NL-TRA methods can be subdivided in two categories as shown below:

- TR-NEWS: NEWS is used as post-processing for conventional time reversal acoustics. It applies to cases where the area of interest is on an accessible surface. The method consists in using conventional TRA to focus energy on scatterers located close to the surface, and then analysing the harmonic content or other nonlinear signatures in the retro-focalised signal. This method has proved to be effective in some cases, but it is of more limited applicability than the NEWS-TR mode described below.
- NEWS-TR: NEWS is used as pre-processing for time reversal acoustics. In this case, NEWS filtering is applied to signals prior to time reversal and re-injection, so that (ideally) only the nonlinear content of each signal is allowed to propagate back into the object. This will result in focusing of energy on sources of nonlinearity only, avoiding undesired focusing on linear sources which tend to ‘overshadow’ the focusing on damage-related scatterers. NEWS-TR was the imaging technique most intensively studied in WP2.2.

Several options of nonlinear signal analysis were investigated for use in the NEWS-TR method, and these are described below:

- Harmonic filtering: this consists in filtering out the linear components of each signal with the use of high-pass or band-pass filters (generally FFT). It results in probably the simplest NEWS-TR experimental procedure since only one set of measurements (i.e.

one 'forward propagation') is required. However, this type of signal processing has some limitations as one would expect from high-pass and band-pass filters.

- Intermodulation frequency filtering: here the nonlinear signatures of interest are the side bands generated by material nonlinearity under bi-frequency excitations. It consists in extracting sum- and difference-frequencies from the signal recorded for each transducer after excitation of the specimen with a bi-frequency 'pulse'. This is followed by time-reversal and re-injection, so that focusing occurs at the nonlinear sources.
- Phase-coded pulse-sequence (or 'pulse inversion') filtering: the specimen is excited and signals are recorded in two separate experiments, using sign-inverted excitation signals in each of them. In a perfectly linear medium, the sum of signals recorded during each experiment cancel out perfectly; in a nonlinear medium, this sum retrieves the even harmonics contained in these signals. The sum-signals for each transducer are then time-reversed and re-injected, again revealing the location of any nonlinear sources.
- Scaled subtraction method: the specimen is excited and signals are recorded in two separate experiments, using signals of same phase but different amplitude in each. Amplitudes are then normalised, and subtraction is performed between signals recorded in each experiment. Since material nonlinearity is manifested as amplitude-dependent behaviour, this subtraction will reveal any nonlinear content in the signals. These subtraction-signals are then time-reversed and re-injected.

4. Feasibility of NEWS localisation and imaging methodologies

This section is a summary of the main outcomes from the development of NEWIMAGE methodologies, presenting conclusions and recommendations for the various aspects investigated in this project.

Recommended NEWS methods for damage localisation and imaging:

- NEWS-TR and its variations have been effectively applied to a number of real and virtual experiments, and remain as the most robust NEWIMAGE methods for medium-sized components investigated in this work. The large number of variables involved (e.g. number and location of transducers and type of signal treatment) may allow for further improvements, especially when tailored to specific cases.

Recommendations regarding number and positioning of transducers in NEWS-TR (Deliverable D10 and Deliverable D9, Section 2b):

- Larger number of transducers results in better focusing on nonlinear scatterers (as compared to the focusing on transducers). Since no filtering procedure is ever perfect, some focusing on the transducers during backward propagation is unavoidable. With larger number of transducers this 'side-effect' is minimised. See Deliverable D9, Section 2b.
- Larger aperture of transducer array (average distance between elements) generates better spatial resolution. This is in accordance with basic linear TRA principles. See Deliverable D10, Section 1.
- Two scenarios have been considered with regard to the physical setup of NEWS-TR as inspection/detection methods:

- permanent (embedded) transducers, for use as in-line structural health monitoring systems;
- removable (contacting) transducers, grouped in arrays, for use as a scheduled inspection equipment.

In the present work, emphasis was given to the development of the method as a whole, so that the principles can be applied to either configuration (embedded or removable).

- There are practical limitations on the number of transducers that can be used, due to experimental complexity and cost. Therefore, it is of interest to enhance the resolution and sensitivity of the method 'via software', i.e. through the development of more effective signal processing methods and iterative procedures, which can expand the capabilities of the method while still relying on a minimal hardware setup.
- There are limitations on the positioning of transducers, especially for removable ones, which depend on the accessibility of the free surfaces of an object. Therefore, studies based on numerical simulation have been performed with these limitations in mind, and the NEWS-TR procedure has shown to be effective even in adverse conditions. See Deliverable D9, Section 1d.
- Optimised procedures and more complex algorithms (e.g. iterative processes) can increase drastically the efficiency of NEWS-TR when the number of transducers and/or the array aperture is limited. This was the main focus of WP2 during the final year of the project: further development and refinement of the methodology was achieved by allowing multiple forward propagation stages, either to reveal weak scatterers, to alternate the location of source and transducers, or to 'scan' the specimen with focused ultrasound energy (Deliverable D9, Section 3). It should be noted that these iterative procedures rely on the same 'hardware' as the basic NEWS-TR procedure, and that iteration is easily performed since excitation/measurements are microcomputer-controlled.

Effects of noise on NEWS-TR recorded signals (Deliverable D9, Section 2a):

- The effects of noise have been studied numerically by the inclusion of random white noise into forward and backward propagation signals. This was done in order to investigate the influence of noise – which is always present in real ultrasonic measurements – on the effectiveness of the NEWS-TR method.
- Noise in signals recorded during the forward propagation had only a small effect on the performance of the method. Nonlinear filtering methods proved to be robust in relation to the presence of this noise.
- Noise in filtered signals, however, affected the image reconstruction considerably. This was expected, since the TRA principles rely on the constructive interaction between multiple signals to reveal the location of the source. This highlights the importance of having good quality electronics for a successful NEWS-TR procedure.
- It was difficult to quantify the effects of noise precisely in the experimental NEWS-TR analyses. For the steering actuator bracket, signals were averaged about 100 times in order to enhance the signal-to-noise ratios to acceptable levels. This might have an impact in the development of NEWS-TR as an embedded structural health monitoring technique. However, this is not the case for the use of NEWS-TR as inspections methods, and the rapid technological development in areas such as microelectronics may lift any restrictions for structural health monitoring as well.

Signal normalisation (Deliverable D9, Section 2c):

- Numerical studies on simple geometries show that normalisation of filtered signals prior to re-injection improves greatly the focusing properties of NEWS-TR, since all transducers contributed more evenly to the retro-focalisation despite the variable levels of amplitude recorded at each transducer.
- However in complex geometries, including the steering actuator bracket, normalisation resulted sometimes in excessive amplification of noise for signals with weak nonlinear contents.
- Therefore, NEWS-TR with or without normalisation of signals should be seen as two complementary procedures, and both should be considered for damage detection in real structures.

'Subtraction processing' (Deliverable D7, Section 1b.1):

- Subtraction processing consists in subtracting the forward propagation signals from a baseline reference (an intact sample) from the signals recorded on the damaged object.
- As one would expect, subtraction processing eliminates focusing on transducers, adding sensitivity to the procedure.
- However, a baseline reference is not very often available; therefore subtraction processing has not been pursued in this project.

Influence of location of damage within the test object (Section 1 (above) and Deliverable D9, Section 1b.2):

- Harmonic filtering is more accurate when the defect is located between the source and the sensor array, due to the higher frequencies involved.
- Pulse inversion filtering is more accurate when the defect is near an edge of the specimen, since this method provides better rejection of the contributions from the bulk.
- Techniques such as wave focusing (during forward propagation) and 'iterative' NEWS-TR may enhance the procedure when the defect is in a remote region within the structure.

Completeness of information (Deliverables D9 and D10):

- Numerical studies on complex 2D geometries indicate that NEWS-TR provides appropriate defect localisation even if transducers can only sense and actuate in one direction (Deliverable D10).
- Simulations on complex 3D geometries show that even under realistic conditions, i.e. transducers sensing/acting only in one direction normal to the surface, NEWS-TR can still be used with relatively good accuracy for locating damage.

Presence of impedance barriers (Deliverable D9, Section 1a):

- Simulations have been performed including strong impedance mismatch layers between source and damage.
- The presence of these layers may affect the procedure considerably.
- Negative effects can be compensated by the use of larger arrays and longer time windows.

Presence of voids (Section 1 (above) and Deliverable D9, Section 1b):

- Large voids may block part of the waves originated at the source from reaching the damage.
- Large voids may also ‘trap’ wave energy between themselves and other surfaces.
- These will result in decreased focusing intensity at the damage site.
- However, good indications of the damage location are still produced.

Geometrical complexity (Section 1 (above) and Deliverable D9, Section 1b and 1c):

- NEWS-TR has been applied successfully to complex 2D and 3D structures.
- Geometrical complexity, specially in 3D, may require larger number of transducers for damage imaging of acceptable resolution.
- However, the presence of damage is identifiable and its relative location can be ascertained if signals are not normalised prior to reinjection.

Presence of multiple scatterers (Deliverable D9, Sections 1c and 3):

- The presence of multiple scatters (or sources) may be an issue if the focusing generated by one source is much weaker than other sources in the system.
- One possible solution is the use of focused waves during the forward propagation stage, to selectively excite certain regions of interest within the object (Deliverable D9, Section 1c).
- Other possibility is the use of iterative time reversal procedures (of multiple forward and backward propagations, i.e. Deliverable D9, Section 3).