## 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

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# Deliverables D20 and D21

D20: Recommendation regarding the use of NEWS method for non-destructive testing in aeronautics

D21: Suggestions for standards in terms of test conditions, device requirements, sensor placements and calibration techniques

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**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)

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# Contents

**1. OVERVIEW OF THE TASKS, DELIVERABLES AND MILESTONE OF THE WP5 ..................... 3**
  2.1 Overall objectives of WP5 ..................... 3
  2.2 Description of WP5 tasks ..................... 3
  2.3 Deliverables, Milestone and expected result of WP5 ..................... 3
**2. REPORT ON THE RECOMMENDATIONS AND SUGGESTIONS REGARDING THE USE OF NEWS METHOD FOR NON-DESTRUCTIVE TESTING IN AERONAUTICS ..................... 5**
  Introduction ..................... 5
  Materials, parts and damage tested during the project ..................... 6
  Nonlinear techniques tested during the project ..................... 7
  Recommendations and suggestions of use ..................... 8
  Specific Nonlinear techniques recommendations ..................... 11
**3. GRADUAL TRANSITION TO SHM SYSTEMS ..................... 32**
**4. CONCLUSIONS ..................... 34**

# 1. Overview of the Tasks, Deliverables and Milestone of the WP5

Overall participants in WP5:

| **Workpackage leaders** | VZLU | |
|---|---|---|
| **Person-months per participant:** | 15 | |

| **Participant id** | KU Leuven | DAKEL | ITASCR | NDTE | BR&TE |
|---|---|---|---|---|---|
| **Person-months per participant:** | 3 | 7 | 3 | 5 | 3,5 |
| **Participant id** | BODY-COTE | UNIV-BRIS | GIP-U* | IZFP* | EXETER * |
| **Person-months per participant:** | 10 | 2 | 4 | - | |

* As the project evolved GIP-U was involved as new partner in WP5 tasks by 4 person months. IZFP and EXETER partners collaborated on WP5 tasks as a fruitful consequence of their activity in WP1 and WP4.

## 2.1 Overall objectives of WP5

- Validation of the efficiency of the NEWS inspection method in operational conditions.
- Installation and testing of a complete inspection system at a testing site.
- Defining requirements for operating the NEWS inspection method in particular environments.
- Formulation of recommendation for the implementation of NEWS for on-ground and in –flight non-destructive testing

## 2.2 Description of WP5 tasks

- WP5.1 Choice of an appropriate site and testing object for validation of the efficiency of the proposed NEWS system.
- WP5.2 Assembling of the complete inspection system on a full scale model at the testing site.
- WP5.3 Test and evaluation at the validation site.

## 2.3 Deliverables, Milestone and expected result of WP5

Apart from the deliverables 17, 18 and 19 that describe in detail the nonlinear inspection systems carry out by the different partners, the scope of this Work Package is to provide with a series of recommendations (Deliverable 20) and suggestions (Deliverable 21) regarding the use of the methods for non destructive testing in aeronautics and the possibility of a future implementation of standards based on nonlinear methods. After the last General Assembly held in Toulouse on February 13-15th, it was agreed that due to the similar contents of these two Work Packages a single document that includes both D20 and D21 would be prepared.

Delivery Date**:** month 48

- D20. Recommendation regarding the use of NEWS method for a non-destructive testing in aeronautics Choice of testing site
- D21. Suggestions for standards in terms of test conditions, device requirements, sensor placements and calibration techniques.

# 2. Report on the recommendations and suggestions regarding the use of NEWS method for non-destructive testing in aeronautics

## *Introduction*

The main objective of the Work Package 5 (WP5) is the implementation and validation of the complete NEWS system on a full scale model of a chosen aircraft structure. WP5 combines the results achieved in WP1 to WP4. Based on that, the goal is to validate the operation of the NEWS technology as inspection system for the monitoring of critical components of structures on a full scale object at a chosen testing site.

The main base of WP5 has been the organization of Experimental Weeks in the facilities of VZLU. As described in previous deliverables, these experimental weeks consisted in the performance in parallel of different NEWS methods. Each participant/partner was responsible for his experimental set-up, and prepared and organized his own measurements. The *Prague Experimental Week I* was held in May 2006. The purpose of that week was to examine realistic samples subject to progressively increased damage. This experience served as a stage between pure laboratory tests and the final full scale tests. Several samples were available for inspection of fatigue damage - a wing lower surface aluminum panel, a model of wing attachment lugs, and impact damaged CFRP single skin samples.

This workshop was followed, one year after, in May 2007, by the *Prague Experimental Week II*. This second week was devoted to validate NEWS techniques as inspection methods for full scale real aircraft parts, as a part of WP5 tasks. During this experimental week, traditional NDT were also used for comparison purposes. In this second occasion, the chosen parts for the experiments were a steering actuator bracket and a fork leg, both belonging to a commuter airplane nose landing gear. In between these two experimental weeks, a special meeting was organized at Exeter University laboratories in January 2007 intended as pre-testing and preparatory experimentation before the validation process in May.

WP5 will display the power and the potential of nonlinear methods when applied under real test objects. WP5 started at month 18 with subtask WP5.1 “Choice of an appropriate site and testing object” for validation of the efficiency of the proposed NEWS system. The Work Package also includes the “Assembling of the complete inspection system” (WP 5.2) and the final “Test and evaluation at the validation site” (WP 5.3).

The choice of an appropriate testing object, fatigue load procedures, choice of suitable NEWS techniques and of the proposed NEWS inspection system constituted a complex problem. Deliverable 17 comprises the final decision taken by the partners involved. Deliverable 18 and 19 summarize the installation processes and the final results obtained. The last two Deliverables, D20 and D21, represent the conclusions extracted from the experience acquired during these four years.

This report will summarize the feasibility of the methods and its advantages and disadvantages as potential SHM systems. It describes general recommendations for the implementation of new methods for structural health monitoring in aviation. These recommendations are based on the results and experienced achieved during the experimental and theoretical work carried out during the development of the project AERONEWS.

The document starts summarizing the materials and samples, structures or parts that have been tested. The nonlinear methods investigated during the project are also listed. Next, individual recommendations for every method are described. The third and last section of this document discusses how technologies like the ones studied under the scope of AERONEWS can be followed up and transferred from laboratory tests to real implementation inside an aircraft.

## *Materials, parts and damage tested during the project*

- **First experiments in each partner's laboratory**

  **Simple samples**
  - aluminum plates with different degrees of fatigue cracks around a perforated hole
  - aluminum plates with chemical corrosion
  - composite panel with delamination
  - composite panel with impact damage
  - composite panel with thermal damage

  **Extended structures and volumetric parts**
  - wing panel with fatigue cracks
  - aluminum panel with rivet faults
  - extended aluminum structure with fatigue cracks
  - extended aluminum structure with chemical corrosion
  - still bracket with fatigue crack
  - ASCO cracked sample
  - Adhesive Joints with incomplete or weak bonding
  - Bi Layers, cracked glass
  - Aluminum fuselage partch
  - PMMA (Polymethylmetacrylate) with Laser Induced cracks
  - slat track

  During the first stages of the project a large variety of materials, samples and damage was distributed and tested among the partners. The summary of the results achieved with these first experiments are described in Deliverable 5. D5 contains the limitations and feasibility of the various method considered during WP1.

- **During the Prague Experimental Week I**

  Fatigue testing:
  - Wing lower surface test panel (aluminum)

- Clevis attachment with two and three lugs (aluminum)

Impact testing:

- CFRP (Carbon Fiber Reinforced Plastic) Plate

- **During the Exeter preparatory meeting and Prague Experimental Week II**

  The two parts chosen for the validation process belong to the nose landing gear of a commuter aircraft. They were subjected to fatigue testing.

  - **Steering actuator bracket** (Czech high performance steel L - ROL, chemical composition of C 0,3; Mn 1,0; Si 1,0; Cr 1,0. Semi product: forging, Hardening treatment: austempering on Rm = 1080 – 1420 MPa).
  - **Fork leg** (Czech high performance steel V - ROL N, chemical composition of C 0,3; Mn 1,2; Si 1,0; Cr 1,0. Semi product: forging, Hardening treatment: austempering on Rm = 1422 - 1620 MPa).

## *Nonlinear techniques tested during the project*

During the development of the project several nonlinear techniques have been tested:

- **During the first stages of the project**

  *Nonlinear techniques*

  1. Higher harmonic generation of a narrowband ultrasonic excitation (IZFP, ITASCR)
  2. Ultrasonic wave mixing (ITASCR, UNIVBRIS, CU)
  3. Nonlinear reverberation spectroscopy (KULeuven)
  4. Nonlinear time reversal acoustics (KULeuven, GIP-U)
  5. High frequency multi-sine broadband excitation (VUB)
  6. Contact phase modulation in bi-layered solids (GIP-U)
  7. Frequency response function technique (UNI-Na)
  8. Nonlinear wave spectroscopy and Third order parametric excitation (CSIC)
  9. Phase-coded pulse sequence technique (BodyCote)

  *Linear validation techniques*

  10. Conventional NDT techniques as reference (NDTE, BodyCote)

- **During the Prague Experimental Week I**

  *Nonlinear techniques*

  1. NEWS (First test of harmonic generation and intermodulation- Exeter)
  2. Bispectrum (UNIVBRIS)
  3. Time Reversal-NEWS (KULAK, GIP-U)
  4. Multisine Lamb Waves (Bodycote)
  5. Double frequency missing-NWMS (ITASCR)

  *Linear validation techniques*

6. Acoustic Emission (ITASCR)

- **During Exeter Meeting and Prague Experimental Week II**
  *Nonlinear techniques*
  1. Nonlinear reverberation spectroscopy (KULAK)
  2. Nonlinear Impact Modulation Spectroscopy (KULAK)
  3. NEWS-Time Reversal (KULAK, GIP-U)
  4. Time Reversal NEWS with chirp (or sweep)-frequency excitation (GIP-U)
  5. Ultrasonic Intermodulation using Bispectral Analysis (UNIBRIS)
  6. Multiple-mode Ultrasonic intermodulation
  7. Harmonic distortion analysis using frequency burst, continuous dual frequency transmission and frequency sweep (chirp). (UNEXE)
  8. Nonlinear Frequency mixing and Multiplexed Time Reversal (ITASCR)

  *Linear validation techniques*
  9. Linear Rayleigh wave measurements (IZFP)
  10. Acoustic Emission (DAKEL, VZLU)
  11. Traditional NDT, Linear Phased Array Ultrasonic (NDT-Expert)

## *Recommendations and suggestions of use*

As it can be seen in the previous sections, the project AERONEWS has examined a large variety of methods, materials, aircraft parts and type of damages. This gives a good foundation to analyze the possible applicability of nonlinear methods in the aeronautical industry as non destructive testing.

The recommendations given by every NEWS method in the following section are based in the following aspects:

1. **The part or material to be tested:**

   During the AERONEWS project both simple and complex structures have been tested. Some simple and small aluminum coupons were tested in the early stages of the project. The next steps consisted in implementing the same techniques on extended structures that simulated the structure of fuselage or wings. In the last phase of the project, the last tests have been performed on specific part that belongs to a landing gear.

   There are limitations inherent to each of the NEWS methods experimented during the project and it is essential that these limitations are known so that the appropriate method will be applied to the appropriate test object in the future. The variability of materials and objects size and shape tested during AERONEWS have helped to analyze which type of material and surface are best suitable for each one of the methods.

## 2. The nature of the failure to be detected

Similar analysis is made in terms of the type of failure the methods can detect. The majority and the main tests have been performed to detected cracks from fatigue damage in metallic structures or parts. Some attempts were also made on composite materials affected by impact damage. The tests performed have helped to analyze for which type of damage the NEWS methods are more effective.

## 3. Threshold of detectability

This topic has already been address in Deliverable 5 (WP1). The higher sensitivity demonstrated by NEWS methods is an important factor to consider. The implementation of these methods in a real aircraft will be determined not only by the automatization of a measurement and the possibility of continuously being capable of analyzing the state of an structure of part, but by the advantages demonstrated against current NDT methods and specially in the ability of detecting smaller defects than those already captured/detected by current NDT techniques.

Recommendations are given to choose which technique is more suitable to use depending on the damage size to be detected.

## 4. Requirements of the equipment needed

Recommendation regarding the equipment to be use for every method will be described. It will be explained the need of using specific devices that must be manufactured for the purpose of NEWS or if conventional and existing commercial equipment can be used. The equipment includes the measurement chain: transducers (actuators and sensors), amplifiers, frequency analyzers, etc.

## 5. Sensor placements

This point aligns with the local or global nature of the method. Recommendations will be done regarding how near the expected damage the sensor must be placed. Some ideas will also be given in terms of the recommended number of sensors for the measurements.

When talking about sensor placement, different contexts have to be considered regarding the position of the damage. For fatigue damage on a metallic part, the initiation point area and the orientation of crack growth are pretty well known after calculations taking into account fatigue load. For impact damage or accidental damage, the suspected damaged area can be very large.

## 6. Variables that can affect the measurement

Some general recommendation will also be given about the variables that can affect the measurement like temperature (that can affect the temperature of transmission of waves or the attenuation), the frequency used and the grain size, the resolution and other variables that have to do with the processing of the signals, the contact pressure of the transducers and the couplant, etc.

## 7. Calibration techniques

The calibration is another important recommendation to take into account when performing NEWS techniques. Aspects related to the possibility of establishing calibration techniques for each of the NEWS methods will be also treated in this section.

In Non Destructive Testing applications, state of the art techniques are using calibration block with representative defects. Those calibration blocks are necessary to calibrate the sensitivity of the technique and to assess the capability of detection, in each particular application (defect location and size, shape and thickness of the part).

Applications dealing with metallic part subject to fatigue crack are using reference standard of same material, shape, thickness and having electro discharge machining notch as a representative defects.

Applications dealing with composite part are using reference standard of same material, shape, thickness and having teflon layer to simulate disbonding.

Those reference standards can’t be used for NEWS technique calibration because non linear techniques require real fatigue crack of known size. Another question that has to be addressed is whether it is possible to have a common calibration block or if we’ll need a calibration block for each specific geometry.

Some techniques based on comparison of nonlinearity from virgin state, will require a undamaged part of the same overall dimension.

Some techniques are sensitive to mounting conditions and will require having records of the same part, in the same mounting conditions before damage.

## 8. Measurement conditions

In view of the tests performed, it will be analyze if the part has to be dismounted or if it could be tested while in service.

## 9. Analysis of results

Some recommendation about the analysis of results can also be given. It will be described if the results depend on operator’s evaluation, if there is a subjective component in analyzing the results, if they can be subjected to interpretation, or if they are clear and objective

## 10. Other

Additional recommendations not included in the previous list that the partners consider relevant for this Deliverable

## *Specific Nonlinear techniques recommendations*

## Method: "Phase-coded pulse sequence technique (PCPS, Bodycote)"

The method "Phase-coded pulse sequence technique" has been presented in the first half of the project as a scheme to extract the nonlinear component of broadband signals. As such it is more a signal processing technique than an inspection configuration. However, the specificity of the method makes it particularly applicable to certain structure configuration such as adhesive bonds. The following presents recommendations for the detection of nonlinearity of adhesively bonded plates.

### The part or material to be tested:

PCPS is recommended for parts that require the use of pulse in order to keep information on propagation time that can be used for localization of the defect. A typical example is the detection of weak bond in multilayered structures. The technique is well suited for the pulse-echo configuration. The technique can be used together with scanning in immersion tank.

### The nature of the failure to be detected

The technique applies to all types of failure that generate a non-linear reflection or scattering when excited by an ultrasonic field.

### Threshold of detectability

In the case of adhesive bonds, the nonlinear response of a bonded joint that had lost 30% of its shear strength due to the contamination was detected. These types of weak bonds are not detectable with linear US techniques.

### Requirements of the equipment needed

The technique requires a function generator to generate the excitation pulse sequence, a power amplifier, one or several transducers, and a receiver. The measurement chain should be as linear as possible. In pulse-echo configuration, the bandwidth of the transducer should be twice as large as the bandwidth of the excitation pulse in order to register the nonlinear component.

### Sensor placements

The same configuration as the one used for "Linear" US NDT can be used.

### Variables that can affect the measurement

The nonlinearity of the contact between the transducer and the part should be constant. In case of scanning, immersion in water provided a constant non-linearity level.

### Calibration techniques

Calibration requires a pristine component and components with different levels of aging. The correlation between aging and nonlinearity level should be determined in advance.

### Measurement conditions

Similar measurement conditions the ones used for "Linear" US NDT apply.

**Analysis of results**

Scanning in immersion tank provides images of the non-linear response over the sample and can be used to localize the defective area.

## Method: "Contact Phase Modulation in bi-layered solids (GIP-U)"

Some special requirements are necessary for nonlinearity evaluation in bi-layered solids

**The part or material to be tested:**

Physical properties of the sample under test must be homogeneous. The sample must be placed between the transducers where the parametric interaction is generated. Thickness of the sample in which the parametric interaction occurs must be higher enough.

**The nature of the failure to be detected**

The nature of nonlinear signature is global classical nonlinearity.

**Excitation strategy**

Single frequency tone burst are necessary in order to avoid multiple reflection.

**Threshold of detectability**

Level of phase modulation index must be grater than 5 mrad.

**Requirements of the equipment needed**

Experimental configuration is relatively simple. Special attention must be carried out for contact transducers.

**Sensor placements**

LF and HF sensors must be placed in front of each other. LF frequency has to be 10 times lower than HF. Contact transducers is preferred.

**Variables that can affect the measurement**

Impedance mismatch between the layers. Bandwidth of the sensors.

**Calibration techniques**

LF transducer calibration is needed for absolute measurements of nonlinearity.

**Measurement conditions**

Measurement of the phase modulation index induced by nonlinear effects versus amplitude of the LF wave.

**Analysis of results**

Digital signal processing for phase demodulation of the HF wave.

## Method: “TR-NEWS method (GIP-U & KULeuven)”

The method “TR-NEWS” has been presented in the second half of the project as a scheme to extract the local nonlinear component in materials containing microscopic surface damage (for instance near surface delaminations, surface breaking cracks, etc). It uses Time reversal method to concentrate high levels of energy at a certain location and analyses the nonlinearity in the received signal as function of the position on the surface.
Some special requirements are necessary for local nonlinearity evaluation of a structure with TR-NEWS

### The part or material to be tested:

The geometrical symmetry of the structure has to be as complex as possible in order to decrease the proportion of energy in the resonant modes.

### The nature of the failure to be detected

The expected area of damage should be at the surface of the sample**.** If a scanning is realized, local nonlinearity can be analysed in a 1D or 2D map.

### Excitation strategy

Burst excitation is usually used. However, chirp-coded excitation can be chosen to increase the signal-to-noise ratio and for a better nonlinearity extraction.

### Threshold of detectability

For metallic sample, the local level of acoustic particle velocity must be higher that 60 mm/s in order to measure nonlinear signature with a 12 bits ADC.

### Requirements of the equipment needed

The experimental configuration is relatively complex. Special attention must be given to the proper synchronization of the emitting devices. Duration of the analysis can be relatively long.

### Sensor placements

The us of multiple sensors is preferred over a single sensor in order to decrease the level of side lobes, and increase the spatial retrofocalication. They can be placed on the same side of the structure to be analysed. Laser measurement is performed on the surface and can be performed even on composites. The area of damage is difficult to localize if it is placed between the transducers. Scanning software is used to perform 2D mapping.

### Variables that can affect the measurement

The acoustic frequency of the initial wave must be chosen in order to increase reverberating response.

### Calibration techniques

Analysis on intact samples should show non nonlinearity. Preliminary experiments must be conducted in order to choose the parameters (frequency, reverberation time) for the acoustic excitation.

### Measurement conditions

- The use of parametric interaction of acoustic waves is preferred over harmonic generation for the nonlinearity evaluation since it helps in excluding the intrinsic nonlinearity of excitation devices from the analysis.
- External synchronization of generators/receiver must be conducted in order to avoid jitter in the inverse and direct responses necessary for performing the extraction of the nonlinearity using the pulse invertion (PI) method

### Analysis of results

Signal processing based on FFT analysis to extract nonlinear spectral components in the received signals.

## Method: “NEWS-TR method (GIP-U & KULeuven)”

The method “NEWS-TR” has been presented in the second half of the project as a scheme to extract the local nonlinear component in materials containing microscopic damage which is buried deep inside. It uses spectral NEWS filtering followed by the time reversal method to concentrate the nonlinear energy at the location of the damage. The analyses of the retrofocalisation of the energy inside the material should be coupled to a wave propagation model of the structure. This allows a mapping of the defect position.
Some special requirements are necessary for local nonlinearity evaluation of structure with NEWS-TR

### The part or material to be tested:

The geometrical symmetry of the structure has to be as complex as possible in order to decrease the proportion of energy in the resonant modes. Investigation of a single area of damage is easier than for multiple scatterers.

### The nature of the failure to be detected

The expected area of the damage can be inside the expected structure. If close to the surface, a scanning can be realized and the local nonlinearity can be mapped. In other cases numerical models should be used for pinpointing the damage location.

### Excitation strategy

Single frequency excitation is prefered in order to localize the source of nonlinearity and decrease diffraction effects. The pulse inversion technique for extracting the nonlinearity must be preferred over harmonic filtering because

- it is experimentally easier to conduct
- PI filtering cancels all linear components, even for a broadband excitation

### Threshold of detectability

Highly dependant of the source of nonlinearity.

### Requirements of the equipment needed

The experimental configuration is relatively complex. Special attention must be given to the proper synchronization of the emitting devices. Duration of the analysis can be relatively long.

### Sensor placements

The use of multiple sensors must be prefered over single sensors in order to decrease the level of side lobes and to enhance the spatial retrofocalisation. They can be placed on the same side of the structure to be analysed. Laser measurement is performed on the surface and can be performed even on composites. The area of damage is difficult to localize if it is placed between the transducers. Scanning software is used to perform 2D mapping.

### Variables that can affect the measurement

The acoustic frequency of the initial wave must be chosen in order to increase the reverberating response. The intrinsic nonlinearity of the transducers which time-reverse the nonlinear components of the signals must be as low as possible.

### Calibration techniques

Analysis on intact samples should show non nonlinearity. Preliminary experiments must be conducted in order to choose the parameters (frequency, reverberation time) for the acoustic excitation.

### Measurement conditions

- The use of parametric interaction of acoustic waves is preferred over harmonic generation for the nonlinearity evaluation since it helps in excluding the intrinsic nonlinearity of excitation devices from the analysis.
- External synchronization of generators/receiver must be conducted in order to avoid jitter in the inverse and direct responses necessary for performing the extraction of the nonlinearity using the pulse invertion (PI) method

### Analysis of results

Signal processing based on FFT analysis, coupled to a wave propagation model of the structure to allow time reversing the signals or tomography analysis.

## Method: “Nonlinear Reverberation Spectroscopy (KULeuven)”

The nonlinear reverberation spectroscopy NRS technique analyses the amplitude dependence of frequency and damping (related to modulus and attenuation) in the reverberating signal of an object when excited at one of its natural frequencies. It is a global technique that can be used for fast diagnosing of damage.

### The part or material to be tested:

NRS is a global technique. The structure has to be able to be put in resonance.
Samples with low intrinsic attenuation are ideal for this technique.

### The nature of the failure to be detected

Any type of failure, with preference to global damage such a thermal cracking. Localized damage is much harder to detect since the wavelength is large compared to the size/spread of the damage.

### Excitation strategy

Non-contact excitation using a loudspeaker, or contact excitation using transducers.

### Threshold of detectability

Global damage is quite easy detectable. For localized damage, it depends on the location with respect to the mode shape under investigation.

### Requirements of the equipment needed

Simple experimental set-up. Preferred is a good ADC (14 bits or more). Duration: approx 5 min total.

### Sensor placements

One sensor is sufficient, placed a some extremity of the sample (where it is unlikely to have a nodal point).

### Variables that can affect the measurement

Since this is a resonance technique the measurement can be affected by the nonlinearities of the support.

### Calibration techniques

Intact materials show a flat line (no amplitude dependence of frequency or damping).

### Measurement conditions

Free support of the object is preferred to avoid contacting nonlinearity. Non-contact excitation and non-contact measurement can be achieved by speaker excitation and laser reception.

### Analysis of results

The reverberation is usually measured in 3-5 feedback steps. The signal is analysed using windowed exponential-sine-fitting, providing the frequency and attenuation properties for each window as function of the amplitude.

## Method: "Nonlinear Impact-Modulation Spectroscopy (KULeuven)"

The nonlinear impact modulation spectroscopy NIMS technique analyses the sidelobe energy versus the impact energy as a result of the impact modulation of a high frequency wave with a low frequency impact. It is a global technique that can be used for fast diagnosing of damage.

### The part or material to be tested:

NIMS is a global technique. The structure has to be able to be put in resonance by a hammer impact. Samples with low intrinsic attenuation are ideal for this technique.

### The nature of the failure to be detected

Any type of failure: global or local.

### Excitation strategy

Impact is generated by a hammer (usually 0-20KHz), also providing the trigger for the measurements. The high frequency excitation is a CW monofrequency signal generated by a contact transducer. The frequency depends on the structure. On of the high frequency modes is generally used (range 150-500 kHz).

### Threshold of detectability

Global damage is quite easy detectable. For localized damage, it depends on the location with respect to the mode shape under investigation. Single cracks of a few mm can be easily detected.

### Requirements of the equipment needed

Simple experimental set-up. Preferred is a good ADC (14 bits or more). Duration: approx 5 min total.

### Sensor placements

Two sensor is sufficient: one for high frequency transmission, the other for low frequency impact, placed a some extremity of the sample (where it is unlikely to have a nodal point).

### Variables that can affect the measurement

Since this is a (semi-)resonance technique the measurement can be affected by the nonlinearities of the support. Also, the frequency of excitation plays a role.

### Calibration techniques

Intact materials show a flat line: no modulation of high and low frequency signal.

### Measurement conditions

Free support of the object is preferred to avoid interfering contacting nonlinearity.

### Analysis of results

The modulation experiment is usually performed 10 times. The high frequency intermodulation signal (sensor 1) and the low frequency impact response (sensor 2) are analysed using windowed fouriertransforms, providing the energy in the side-bands of the high frequency spectrum (intermodulation) as function of the energy of the impact.

## Method: “Harmonic generation in steel actuator bracket” (Exeter University)

### Introduction:

Non linear effects evaluated by:-
Single pure tone transmission in to test object, detecting harmonics

### The part or material to be tested:

Steel actuator bracket

### The nature of the failure to be detected

grain microstructure damage
onset of cracking

### Threshold of detectability

Lower limit of distortion measurement is 1.8% (2nd Harmonic)
Lower limit of distortion measurement is 0.4% (3nd Harmonic)
2nd harmonic above 2.8% (indicates serious defect, crack formation)
3rd harmonic above 2.3% (indicates serious defect, crack formation)

### Requirements of the equipment needed

NBOX module 1 transmitter linked to signal generator
NBOX module 2 receiver

### Sensor placements

Transmitter placed one side, receiver on the other.
Test performed through the thickness of the material.

### Variables that can affect the measurement

Contact pressure constant and gel couplant,
Necessary to hold the transducers in place for the test.
Object geometry, necessary to find good flat region
Back ground acoustic interference
Ambient electrical interference, test object earthed to reduce electrical interference and pickup.

### Calibration techniques

Test block used made from steel
Signal level checks, both transmit and received.

### Measurement conditions

Component removed, stand alone tests.
Received signal levels adjusted between 60 to 90% full scale.
Low level will produce a poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

### Analysis of results

Harmonics
Spectrum analysis by FFT graphical plot
Windowing applied on the recorded data (Hamming window)
Level of fundamental to 2nd 3rd and 4th harmonics compared
A value determined by measurement from spectral plots
Harmonics expressed as either dB down from fundamental or as a percentage of the fundamental.
Fast evaluation, one sample taken (data length 100 microseconds), software computes spectrum and displays on screen. Data can be saved for further evaluation.

# Method: “Harmonic and sideband generation in steel actuator bracket” (Exeter University)

**Introduction:**

Non linear effects evaluated by:-
Dual frequency transmission in to test object, detecting side bands and harmonics

**The part or material to be tested:**

Steel actuator bracket

**The nature of the failure to be detected**

Grain microstructure damage, onset of cracking

**Threshold of detectability**

lower limit of distortion measurement is –48dB (0.4%)
below –40dB (1.0%) suggest the material is good
values –35dB (1.8%) to – 40dB (1.0%) suggest onset of degradation
values –30dB (3.2%) to –35dB (1.8%) suggest damage
above –30dB (3.2%) suggest serious damage, cracking

**Requirements of the equipment needed**

NBOX module 5 for dual frequency transmitter
NBOX module 2 for receiver

**Sensor placements**

Transmitter placed one side, receiver on the other.
Test performed through the thickness of the material.

**Variables that can affect the measurement**

Contact pressure constant and gel couplant,
Necessary to hold the transducers in place for the test.
Object geometry, necessary to find good flat region.
Back ground acoustic interference
Ambient electrical interference, test object earthed to reduce electrical interference and pickup.

**Calibration techniques**

Test block used made from steel
Signal level checks

**Measurement conditions**

Component removed, stand alone tests.
Received signal levels adjusted between 60 to 90% full scale.
Low level will produce a poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

**Analysis of results**

Harmonics and upper sideband

Spectrum analysis by FFT graphical plot. Hamming window applied to the data.
Level of fundamentals to 2nd harmonics of the two frequencies compared also level of upper sidebands. The values determined by measurement from spectral plots
Harmonics and sidebands expressed as dB down from fundamental or as a percentage of the fundamental. Fast evaluation, one sample taken (data length 100 microseconds), software computes spectrum and displays on screen. Data can be saved for further evaluation.

## Method: "Harmonic generation in Carbon composite wing" (Exeter University)

**Introduction:**
Non linear effects evaluated by:
Single pure tone transmission in to test object, detecting harmonics
Wing panel progressively subject to impact damage at a single point.

**The part or material to be tested:**
Carbon composite wing panel

**The nature of the failure to be detected**
Micro-cracking and delamination

**Threshold of detectability**
Lower limit of distortion measurement is 1% (2nd and 3rd Harmonics)
2nd harmonic above 3% (de-lamination)
3rd harmonic above 3% (micro-cracking)

**Requirements of the equipment needed**
NBOX module 1 transmitter linked to signal generator
NBOX module 2 receiver

**Sensor placements**
Test performed on one side over surface of material
Transmitter and receiver placed either side of defect (optimum performance)

**Variables that can affect the measurement**
Contact pressure constant and plastic dry couplant,
Necessary to hold the transducers in place for the test.
Back ground acoustic interference
Ambient electrical interference
Composite non conductive, unable to earth.

**Calibration techniques**
Test strips used made from damaged carbon fiber.
Signal level checks, both transmit and received.

**Measurement conditions**
Component removed, stand alone tests.

Received signal levels adjusted between 60 to 90% full scale.
Low level will produce poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

**Analysis of results**
Harmonics
Spectrum analysis by FFT graphical plot
Windowing applied on the recorded data (Hamming window)
Level of fundamental to 2nd 3rd and 4th harmonics compared
A value determined by measurement from spectral plots
Harmonics expressed as either dB down from fundamental or as a percentage of the fundamental.
Fast evaluation, one sample taken (data length 100 microseconds), software computes spectrum and displays on screen. Data can be saved for further evaluation.

## Method: "Harmonic generation in Aluminium wing panel" (Exeter University)"

**Introduction:**
Non linear effects evaluated by:-
Single pure tone transmission in to test object, detecting harmonics
Comparison between small and large crack

**The part or material to be tested:**
Aluminium wing panel assembly.

**The nature of the failure to be detected**
Crack small (9mm) and large (16mm)

**Threshold of detectability**
Lower limit of distortion measurement 0.28% (2nd and 3rd harmonics)
Small crack 0.3% (2nd and 3rd harmonics)
Large crack 1% (2nd and 3rd harmonics)

**Requirements of the equipment needed**
DAKEL transducer glued to wing panel (transmitter) driven by signal generator and power amplifier
NBOX module 2 receiver

**Sensor placements**
Test performed on one side over surface of material
Transmitter and receiver placed either side of crack

**Variables that can affect the measurement**
Receiver contact pressure constant and plastic dry couplant,
Necessary to hold the transducers in place for the test.
Transmitter glue to wing panel

Back ground acoustic interference
Ambient electrical interference
Wing panel connected to earth.

**Calibration techniques**

Signal level checks, both transmit and received.

**Measurement conditions**

Component removed, stand alone tests.
Received signal levels adjusted between 60 to 90% full scale.
Low level will produce poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

**Analysis of results**

Harmonics
Spectrum analysis by FFT graphical plot
Windowing applied on the recorded data (Hamming window)
Level of fundamental to 2nd 3rd and 4th harmonics compared
A value determined by measurement from spectral plots
Harmonics expressed as either dB down from fundamental or as a percentage of the fundamental.
Fast evaluation, one sample taken (data length 100 microseconds), software computes spectrum and displays on screen. Data can be saved for further evaluation.

## Method: “Harmonic and sideband generation in Aluminium wing fuselage attachment (Exeter University)”

**Introduction:**

Non linear effects evaluated by:-
Dual frequency transmission in to test object, detecting side bands and harmonics

**The part or material to be tested:**

Aluminium wing fuselage attachment

**The nature of the failure to be detected**

Large crack

**Threshold of detectability**

Lower limit of distortion measurement is –45dB (0.6%)
Distortion due to crack is 1.3% (2*f1), 3.2% (f1+f2), 3.2% (2*f2)

**Requirements of the equipment needed**

NBOX module 5 for dual frequency transmitter (f1 and f2)
NBOX module 2 for receiver

**Sensor placements**

Transmitter placed one side of crack, receiver on the other.

Test performed over surface of the material.

**Variables that can affect the measurement**

Contact pressure constant and gel couplant,
Necessary to hold the transducers in place for the test.
Object geometry, necessary to find good flat region.
Back ground acoustic interference
Ambient electrical interference, test object earthed to reduce electrical interference and pickup.

**Calibration techniques**

Test block used made from Aluminium
Signal level checks

**Measurement conditions**

Component removed, stand alone tests.
Received signal levels adjusted between 60 to 90% full scale.
Low level will produce a poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

**Analysis of results**

Harmonics and upper sideband
Spectrum analysis by FFT graphical plot
Windowing applied on the recorded data (Hamming window) to improve observation
Level of fundamentals to 2nd harmonics of the two frequencies compared
also level of upper sideband.
The values determined by measurement from spectral plots
Harmonics and sidebands expressed as dB down from fundamental or as a percentage of the fundamental.
Fast evaluation, one sample taken (data length 100 microseconds), software computes spectrum and displays on screen. Data can be saved for further evaluation.

## Method: “Pulse inversion response in steel actuator bracket” (Exeter University)

**Introduction:**

Non linear effects evaluated by:-
Summing two pulses one a tensile pulse the other a compressional pulse.

**The part or material to be tested:**

Steel actuator bracket

**The nature of the failure to be detected**

Grain microstructure damage
Onset of cracking

### Threshold of detectability

Not quantified yet, insufficient experimental data.

Initial observations show that if any of the summed values exceeds 10% of the maximum amplitude of either the compressional or tensile pulse in the sum amplitude-time plot a defect condition is indicated.

### Requirements of the equipment needed

NBOX module 1 the programmable pulse transmitter
NBOX module 2 the receiver

### Sensor placements

Transmitter placed one side, receiver on the other.
Test performed through the thickness of the material.

### Variables that can affect the measurement

Contact pressure constant and gel couplant,
Necessary to hold the transducers in place for the test.
Object geometry, necessary to find good flat region.
Back ground acoustic interference
Ambient electrical interference, test object earthed to reduce electrical interference and pickup.

### Calibration techniques

Test block used made from steel
Signal level checks

### Measurement conditions

Component removed, stand alone tests.
Received signal levels adjusted between 60 to 90% full scale.
Low level will produce poor resolution spectra. High level will cause the amplifiers to over drive and saturate (clip) and thus produce false harmonics in the data. Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven)

### Analysis of results

Clear indication given of the signal level displayed as a graphical plot resulting from the sum of response to the positive and negative going pulses applied to the test object. (Quantitative values have yet to be determined with more experimental data).

Fast evaluation, two pulse samples taken (data length 100 microseconds), software adds time domain data and displays on screen the summed value.

# Method: "Resonant frequency shift steel actuator bracket" (Exeter University)

**Introduction:**

Non linear effects evaluated by:-
Resonant frequency shift with amplitude

**The part or material to be tested:**

Steel actuator bracket

**The nature of the failure to be detected**

Grain microstructure damage
Onset of cracking

**Threshold of detectability**

Not quantified yet, insufficient experimental data.

Initial observations show that if the frequency deviates by more than 2Hz during an amplitude decay of value 10 volts to 1 mV, in the frequency time plot, a defect condition is indicated.

**Requirements of the equipment needed**

NBOX module 10 transmitter (air coupled loudspeaker)
NBOX module 7 receiver (phase locked loop frequency meter)
DAKEL transducer glued to test object and connected to input of NBOX7
Test object suspended on a thin wire.

**Sensor placements**

Transmitter speaker placed 10mm from one side.
Receiver transducer glued to other side.
Sensor placement not critical.

**Variables that can affect the measurement**

Quality of glued coupling.
Back ground acoustic interference
Ambient electrical interference.

**Calibration techniques**

Test block used made from steel
Signal level checks

**Measurement conditions**

Component removed, stand alone tests. Object suspended on thin wire.

Signal levels received set to maximum (10V), over driving the receiver is not a problem with this phase locked loop system.

Transmission levels set within the dynamic range of the power amplifiers (ie, not over driven). Method not sensitive to distortion as the driving oscillation is turned off and the resonating objects amplitude is measured as it decays over a period of time.

### Analysis of results

Observation of frequency shift from a graphical plot, immediate evaluation.
Plotting time depends on object size and material (resonant decay period)
Repeats of bringing to resonance and measuring decay frequency is a simple process.
Comparison with good and bad samples, good sample produce no frequency shift during decay. (quantitative values have yet to be determined with more experimental data).

## Method: “Ultrasonic Intermodulation (UnivBris)”

### Introduction:

The intermodulation of two continuous ultrasonic signals applied to a sample of interest has been used as a measure of non-linearity. The bispectral analysis signal processing technique was used to measure the increase in signal at either the sum or the difference of the two applied frequencies due to damage in the system.

### The part or material to be tested:

The technique allows global inspection of low-attenuation volumetric parts. It has been demonstrated on simple steel beams and also more geometrically complex parts such as the steering actuator bracket.

### The nature of the failure to be detected

The technique has been used to detect fatigue cracks in metals.

### Threshold of detectability

Through cracks in steel components of 6-8% of the cross sectional area were detected. A thumb nail crack of 15% cross section was detected in the steering actuator bracket. Some results suggested that pre-crack microdamage could be detected in certain samples, but this was not confirmed.

### Requirements of the equipment needed

The actuators and sensors used were cheap 5mm-diameter 2mm-thick PZT disks. Generation and detection was achieved with a combined arbitrary-function-generator/oscilloscope. The generated signal used 14 bit accuracy at 10 MHz and detection used 12 bit accuracy at 5 MHz sampling rate. Depending on the sample geometry, size and attenuation some amplification of the signal may be required before it is applied to the actuator, this requires a power amplifier with good linearity.

### Sensor placements

The method is global and the intention is to insonify the entire sample (multiple excitation frequencies are used to ensure good coverage). Provided that this can be achieved the position of the sensors is not critical. Typically two transducers (one generating the signal and one receiving) have been used, but extra transducers could be used to improve coverage or separate the excitation frequencies.

### Variables that can affect the measurement

Selection of excitation frequency is the most important factor in performing the test, but once the appropriate frequencies for a given sample geometry are determined they should remain appropriate unless there is a substantial change in geometry or sensor behaviour. Frequencies are selected to excite resonances of the sample (to maximize response); a sufficient number should be used to ensure good coverage of the sample and a statistically significant number of measurement pairs. The frequency used for non-linear measurement (either the sum or difference of the applied signals) should fall within the sensitivity range of the sensor.

### Calibration techniques

The technique was applied as a baseline comparison method i.e. the mixing for a damaged sample was compared to that either of an identical, but undamaged sample, or to a measurement taken before the tested sample was damaged.

### Measurement conditions

Due to the global excitation of the part it should be ultrasonically isolated from other objects, usually by dismounting.

### Analysis of results

Currently the detection method is to look for an increase in the mean signal at the mixing frequency. This provides a straightforward measure of the increase in the nonlinearity of the sample. Part of the calibration for a particular part would be to determine a threshold value for further testing or replacement.

The use of the mean allows for straightforward analysis of initial results, but more sophisticated statistical analysis may be developed to make better use of the full data available.

## Method: "Multiplexed Frequency Mixing (ITASCR)"

### Introduction:

The method is similar to two-frequency intermodulation procedure, with the difference, that an array of transmitting/receiving piezoelectric transducers is properly dislocated on a structure. Two semi-continuous ultrasonic signals of two different frequencies $f_{low}$, $f_{high}$ are transmitted to a tested sample, one of them with a constant and second with gradually growing amplitude, and their mixing products (side-bands around $f_{high,}$ 2 $f_{high,}$ 3 $f_{high}$) are evaluated as a measure of system nonlinearity. One or both signal transmitters (exciters) are successively multiplexed between receiving transducer array, and the most pronounced mixing products growth specifies defective zone.

### The part or material to be tested:

The technique allows global detection and zonal localization of crack-like damages in both relatively small and large extended thin sheets and volumetric parts of any form. It has been demonstrated on a riveted wing skin panel (Al-sheet), high strength steel landing gear fork leg (curved tubular part), and landing gear steering actuator bracket (flat steel part of complex form).

### The nature of the failure to be detected

Fatigue crack arising from a rivet in Al-Alloy sheet.
Fatigue crack in high strength steel tubular part
Fatigue crack in a flat steel part

## Threshold of detectability

Threshold of detectability was not verified as only 3 different parts with fixed-length fatigue cracks were tested. The smallest detected hair-crack length was 2.1 mm, which resulted in nonlinearity index ratio about 10 dB compared to intact sample.

## Requirements of the equipment needed

A set of piezoelectric transducers with appropriate frequency characteristics, allowing to be switched as actuator and/or sensor (array of up to 8 transducers was used in testing). Number of preamplifiers (20-60 dB with 20kHz high-pass filters) corresponding to used transducers. Two sine-wave generators (20-1000 kHz) with remote amplitude control, and two power amplifiers supplying selected actuators. Multi-channel high-voltage multiplexer switching between actuators and sensors. Multi-channel digital signal recorder, and driving computer.

## Sensor placements

The method can be used as global, covering the whole tested structure with a possibility to specify damaged zone more closely. We can suppose, that the observed mixing products are more pronounced when the excitation sources are closer to damaged zone and wave path of higher excitation frequency comprises present defects. Providing that the source of $f_{low}$ is not multiplexed (lower frequency is less attenuated), it can be placed at any position inside a tested region, and receiving transducers, multiplexed with the source of $f_{high}$ signal are uniformly dispersed (if possible in a quasi-symmetric array) along critical zone. Three or higher number of receiving/transmitting transducers are used to cover relatively large structures, the number of transducers depends on structure extent and attenuation. Maximal distance between transducers should be determined from $f_{high}$ attenuation measurements. All transducers must be well fastened to the structure to avoid nonlinearity at their contact.

## Variables that can affect the measurement

Proper selection of both excitation frequencies is the most important factor in performing the test. The selection depends on used transducers, structure geometry, and measured attenuation. Most suitable frequencies can be determined by calibration procedure (frequency wobbling). $f_{high}$ should be 5 to 10 times higher than $f_{low}$ but the frequency ratio must not be an integer. Selected frequencies needn't to excite resonances, although they should be well detectable by distant transducers even at minimal excitation amplitudes. Excitation amplitudes should be as high as possible but not exceeding certain limits, given by nonlinearities of devices (transducers, preamplifiers and power amplifiers). Another variable affecting results is the length of recorded signal. It should be long enough as to ensure good spectral resolution.

## Calibration techniques

A calibration procedure must be performed before testing. The procedure comprises determination of appropriate transducers placement and excitation frequencies with respect to geometry and attenuation of the structure, and frequency bands of used transducers. Procedure can be realized by frequency wobbling or by the chirp pulse transmission. Excitation amplitude range and steps of amplitude growth must be also properly determined. The best solution is parallel calibration on an intact part.

### Measurement conditions

No specific measurement conditions are needed except of ultrasonic and/or electric noise-free environment. All test conditions (structure mounting and border conditions) must be the same as in calibration measurement on the comparative (intact) part.

### Analysis of results

In a first step, frequency semilog-spectra of all signals received by all transducers are computed and amplitudes of $f_{low}$, $f_{high}$ harmonics and their intermodulation side bands are extracted ($f_{low}$, $2f_{low}$, $3f_{low}$, $f_{high}$, $2f_{high}$, $3f_{high}$, $f_{high}\pm f_{low}$, $f_{high}\pm 2f_{low}$, $f_{high}\pm 3f_{low}$, and similar with $2f_{high}$ and $3f_{high}$). Then, the extracted values are normalized on growing $f_{low}$ amplitude, and regression coefficients of their growth are evaluated (negative means decay and positive increase). The coefficients are compared to that obtained on calibration sample. One of the highest coefficient differences (tested - calibration, in dB) is selected to nonlinearity characterization (nonlinearity index), and ordered to corresponding $f_{high}$ transmitters. Positive differences signalize presence of damage, and their dependence on $f_{high}$ source roughly demarks damaged zone. The correlation of nonlinearity index with damage extent was not studied because of lack of relevant data.

## Method: “Multiplexed TR-NEWS Tomography (ITASCR)”

### Introduction:

The method is a multi-transducer variant of TR-NEWS, similar to previous, multiplexed frequency mixing procedure. Larger array of transmitting/receiving piezoelectric transducers is used to excite the tested structure by mono- or poly-frequency pulses of step-by-step increasing amplitude (received as direct signals). Transmitters are successively multiplexed in transducer array. Direct signals are time reversed (TR) and sent back by original receivers to original transmitters. Spectra of back-received TR signals and their sums are evaluated in dependence on direct transmitted amplitudes. Phase shifted signals are also transmitted along with the direct ones in a more complicated variant of that method. They are also time-reversed, sent back, and spectra of their back-received counterparts are then subtracted from not shifted equivalents. Harmonics growths or other parameters (there is a lot of data processing possibilities) are evaluated as measures of system nonlinearity, and their most pronounced values, ordered to original transmitters, specify defective zones.

### The part or material to be tested:

The technique allows global detection and zonal localization of crack-like damages in both relatively small and large extended thin sheets and volumetric parts of any form. More variants of the method with variable data processing were tested on the same aircraft parts as Multiplexed Frequency Mixing (wing skin panel, landing gear fork leg, and steering actuator bracket).

### The nature of the failure to be detected

Fatigue crack in the wing skin panel, fork leg, and steering actuator bracket.

### Threshold of detectability

Threshold of detectability was not verified as only 3 different parts with fixed-length fatigue cracks were tested The smallest detected hair-crack length was 2.1 mm, with similar to Multiplexed Frequency Mixing results - nonlinearity index about 10 dB (without comparing to any calibration sample).

### Requirements of the equipment needed

An array of piezoelectric transducers with appropriate frequency characteristics, allowing to be switched as actuator and/or sensor (up to 8 transducers were used in tests). Number of preamplifiers (20-60 dB with 20kHz high-pass filters) corresponding with number of transducers. One arbitrary waveform generator (80-1000 kHz) with remote amplitude control, and one power amplifier supplying selected actuator. Multi-channel high-voltage multiplexer, switching between actuators and sensors. Multi-channel digital signal recorder (at least 10 MHz/12 bit, 20 kSamples/channel), and driving computer.

### Sensor placements

The method can be used as global, covering the whole tested structure, and damaged zone localization is more straightforward than in the case of Multiplexed Frequency Mixing procedure. Test results shown that derived nonlinearity index is dependent on the wave path along damaged zone (higher when crossing area with defect). Transducers should be placed at positions surrounding tested area (if possible in a quasi-symmetric way). Four or higher number of transmitting/receiving transducers are necessary to cover relatively large structures. Higher number of transducers gives better results and more accurate defect location. Maximal distance between transducers depends on structure attenuation in selected frequency band. All transducers must be well mounted on the structure surface.

### Variables that can affect the measurement

An important factor is proper selection of the direct excitation pulse frequency (or frequency band), waveform, and amplitude range. Most suitable frequencies can be determined by calibration procedure (chirp pulse or frequency sweeping). Excitation amplitudes (with max/min ratio 5-10) can be lower than in frequency mixing, but sufficient to excite distant transducers. The length of recorded signal also affects the measurement results.

### Calibration techniques

Tests of ultrasonic pulse-wave transfer between transducers should be performed before the measurement as to optimize pulse frequency and shape with respect to geometry and attenuation of the structure, and fall into frequency bands of used transducers. Excitation amplitude range and steps of amplitude growth must be also properly determined. Good, but not necessary is to perform calibration on an intact part.

### Measurement conditions

No specific measurement conditions are needed except of ultrasonic and/or electric noise-free environment. All test conditions (structure mounting and border conditions) must be the same as in calibration measurements.

## Analysis of results

The extent of data obtained from one test depends on number of direct transmitted signals (number of transducers, phase shifts of original pulse, number of amplitude steps, optional procedure iteration - i.e. multiple back and force transmitting, signal averaging to S/N enhancement, etc). Relatively simple data treatment include summation of all TR signals received back by individual sensors (linearity control of the source signal reconstruction), analysis of harmonics growth (e.g.) subtraction of phase-shifted signals and their sums with or without selective filtration, spectral analysis with subtraction of spectra obtained at the higher and lower amplitude, time-frequency analysis, etc. The simplest data evaluation used in performed experiments was nonlinearity index determination as the amplitude dependent growth rate of the $3^{rd}$ over the $2^{nd}$ harmonics ratio. There is a large variety of different treatments, and the most appropriate data processing should be determined in future studies (it seems to be individual for different structures). Derived nonlinearity indexes are stored in a matrix corresponding to transmitters and receivers, and the matrix is treated in a ways similar to tomography as to determine damaged zone location. The advantage of the described procedure is in lower amplitudes necessary to excite nonlinearities, and in its potentiality to acquire complex information on the tested structure.

# 3. Gradual transition to SHM systems

NEWS techniques are capable of achieving continuous monitoring; however, the key aspect now is to translate the results obtained in laboratory conditions to an industrial environment. The development stage differs from method to method; however, the general degree of maturity of SHM systems is sufficient to start focusing on how to implement all those innovative concepts as testing tools acting in operational conditions.

The implementation of SHM systems requires the consolidation of several issues that are still in a laboratory level:

- Reliability of the system.
- Feasibility
- The certification process will be complex. The system will not only have to follow all the written procedures to be certified as allowed device to be integrated in the aircraft structure, but this new systems constitute a change in the classical maintenance philosophy, and many other maintenance procedures would have to be adapted.
- The gain in cost effectiveness of such systems will have to be demonstrated (savings in maintenance, etc).

To consolidate the mentioned issues, and before a SHM system can be developed in an industrial scale and implemented as part of the initial design of an aircraft, the following gradual plan is proposed:

- **Phase I:** Initially, NEWS techniques could be used as comparison methods with existing non destructive techniques. This would allow the improvement of the NEWS methods. This could be performed as part of the normal maintenance processes, traditional and new techniques could be tested in parallel.

  This first phase could help to confirm the performance of the method, its reliability, its limitations and its advantages compared to traditional non destructive techniques.

- **Phase II:** After the first phase of comparison, a second stage in the process could consists in the use of NEWS methods to complement manual inspections. In this case, they would really assist in the process of regular inspections, substituting present methods in those cases where it had been demonstrating (phase I) that the method improves the performance of existing traditional methodologies.

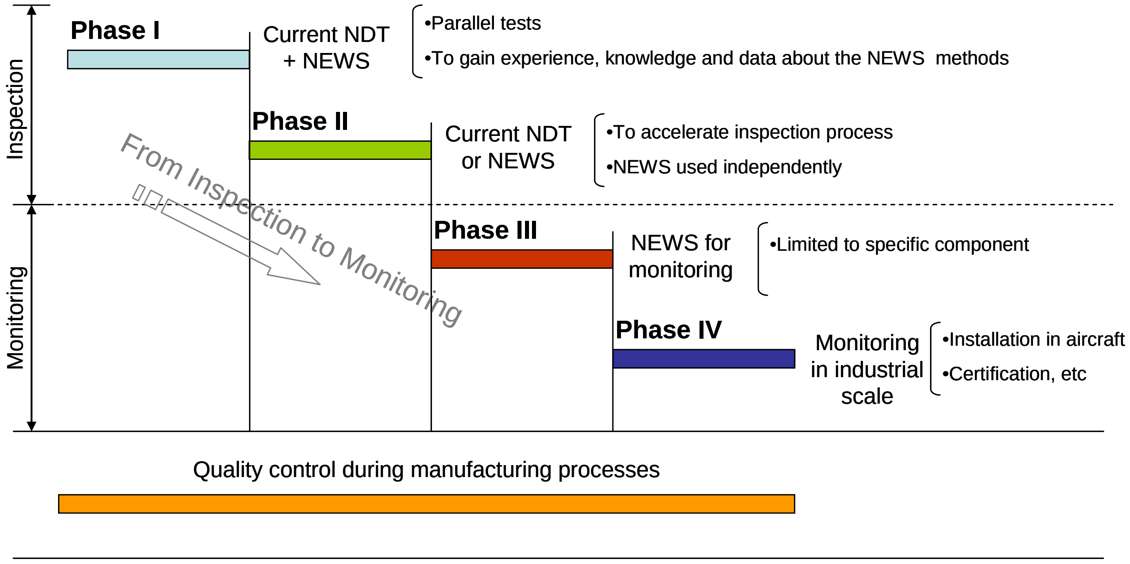
- **Phase III:** In a third phase, the NEWS methods would start acting as monitoring systems. This could be performed over a limited set of components whose life cycles are well understood. This could also help to collect important set of service data of the components.

- **Phase IV:** Once the method has been largely tested following the steps we propose here, there would be a possibility for the airline (or manufacturer) to proceed with the complete implementation of the system in large scale and inside an aircraft.

- **Additionally**, it has also been considered the possibility of using NEWS methods as quality control. The presence of undetectable damage that can be introduced during the manufacturing process is one of the concerns in the design of structures or parts for aircrafts. The concern increases greatly in the case of composite materials. NEWS techniques might serve as controlling techniques for damage detection in production lines. In the case of composites, a hidden damage can produce a significant reduction of the strength of the structure. A reliable inspection technique can be very valuable in these stages of production. It would allow the definition of different damages that can occur in the structure. NEWS technique could in this way be tested in various as well as real damage situations.

  In the case of metallic structures, the concept would be different. Fatigue cracks, which are the main damage studied during this Project, are not the type of defects that can occur during manufacturing processes. In this case, another different study should be performed. An analysis would be needed to study if the principles NEWS techniques are based on can be adapted to the detection of typical defects occurring during the manufacturing in metal parts or structures.

The following graph summarizes the ideas explained above:



# 4. Conclusions

Nonlinear techniques can be applied to very different type of parts. As described in section 2, some methods require simple geometries and flat surfaces to obtain a good performance; in some other cases, complex geometries are recommended.

Regarding the type of failures that can be detected, the Aeronews project has been mainly focused on fatigue cracks. Some methods can be applied to any type of failure that can emit nonlinearities when excited with ultrasound. Some prefer well localized damage, while others are more suitable to generalized damage in an area, like thermal cracking. Depending on the method, the damage can show in the surface of the part of in the interior.

More experiments in a larger amount of parts would have to be performed to have clear figures about thresholds of detectability. In spite of this, in some cases the results have shown a clear higher sensitivity than linear ultrasound. Sometimes the detectability depends on the source of nonlinearity.

The complexity of the experimental configuration differs also from method to method. In most of the cases, existing commercial measurement devices have been used. However, particular sensors and hardware have been specifically designed and manufactured within the consortium for the purpose of Aeronews.

The number of transducers/sensors is key in the measurements. One single sensor is enough in some cases, although multiple sensors are often preferred. Depending on the method the position of the sensors also differs. They must be located on one of the surface of the part to be examined. Sometimes transmitter and receiver should be in different sides of the part or the crack. For global methods, the position of the sensors is not critical.

In general calibration has been performed by preliminary tests on the same type of part but intact (or the same part but before damaged); sometimes the level of the signals acquired in extra test blocks have been used as calibration. Part of future calibration processes would consist in determining threshold values above which a certain increase of nonlinearity represents the presence of damage.

It is important to take into account that some variables can affect the measurements. Special attention must be taken to the nonlinearity of the contact between the transducers and the part, or the nonlinearity of the transducer itself. The frequencies used in the measurement are also fundamental part in the measurements; they must be adapted to the type of part to be analyzed. Electrical interferences can also affect the experiments.

It can be concluded that a large amount of experimental data has been collected during the project. The experiments have demonstrated that nonlinear techniques can be applied to a large variety of parts; however every method is suitable of a certain part and material. It is also necessary to have a good understanding/knowledge beforehand of the piece to be inspected: vibration modes, attenuation, behavior without the presence of damage, etc. We count on good initial results. Some aspects will still need to be consolidated in order to transfer the acquired knowledge from a laboratory level to an industrial environment.