NDETECTION AND LOCALIZATION OF DEFECTS IN COMPLEX STRUCTURES BY NONLINEAR ELASTIC WAVE SPECTROSCOPY AND ACOUSTIC EMISSION

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OUTLINE

1. Motivation: Damage detection - ultrasonic NDT
2. Two NEWS methods (NWMS, NLTRM)
3. AE monitoring and Comparison of AE and NEWS
4. Fatigue testing of aircraft parts (wing flange)
5. Evaluation of Corrosion processes
6. SHM of civil structures
7. Using TR procedure for AE signal deconvolution (TRAED)
Two ultrasonic NDT methods combined in SHM of complex structures

1. Acoustic Emission (AE) - Enables real-time source detection
2. Nonlinear Elastic Wave Spectroscopy (NEWS) AE source verification
(3. Guided Waves implementation)

Employment of both methods is highly effective

**Advantages:**

- Both methods use the same arrays of piezoelectric transducers
- Common devices are used (NEWS needs additional AWG, MUX, and Power Amplifier – used also in AE calibration & processing)
- Both allow localize defects arising in critical parts
  - AE - needs structure stimulation
  - NEWS - applied without stimulation but needs structure excitation
Nonlinear Elastic Wave Spectroscopy (NEWS)

2 NEWS METHODS USED:
a) Multiplexed Nonlinear Wave Modulation Spectroscopy (NWMS)
b) Multiplexed Nonlinear Time-Reversal Mirrors (NLTRM)

Nonlinear effects (NL):
a) Amplitude dependent inter-modulation side bands, odd harmonics growth
b) TR-ESAM derived 3rd order nonlinearity parameter

- Localization of defective zones in NWMS & NLTRM (Pseudo-Tomography)
- Structure excitation using ESAM in NLTRM
Nonlinear Wave Modulation Spectroscopy (NWMS)

Interaction of an elastic wave with a nonlinear scatterer - induces localized wave distortion and simultaneous nonlinear wave mixing, producing higher harmonics, intermodulations, etc.
Nonlinear parameters in NWMS procedure are e.g. growths of higher harmonics $n^*f_1$, $n = 2...7$ and side-bands $n^*f_1\pm m^*f_2$ with growing excitation amplitude $a(f_1)$.
Time reversal in nonlinear medium

Nonlinear Time-Reversal Mirrors (NLTRM)

- In linear media: TR signal is symmetric, with a perfect reconstruction of the original excitation (principle of superposition is valid)
- In presence of nonlinearities in tested medium, the reciprocity principle is broken and also the symmetry of TR signals
- More iterations of TR yield stronger nonlinearity signatures

Initial excitation

Rebroadcast Time Reversed signal (side lobes)
Two different implementations of TR:

a) source emission

b) standard TR

c) reciprocal TR.

PRINCIPLES OF TRM

\[ \Phi(\vec{r}_0, t) = \sum_{j=1}^{N} h_j(t) * h_j(-t) \]

Nonlinear Time-Reversal Mirrors (NLTRM)
ESAM – Excitation Symmetry Analysis Method


• Nonlinearity can be characterized by parameter $N_3$ extracted using simple assumption

• Permits extraction of a nonlinear parameter – coefficient $N_3$ from the nonlinear response $y$ to the excitation $x$. The response is considered to be a 3rd order polynomial function of the input $x$:

$$y(t) = N_1 x(t) + N_2 x^2(t) + N_3 x^3(t)$$

• 3 Excitations (phase shifted) corresponding to the irreducible representations of point group $C^3$ are used for nonlinear part extraction:

$$x_E(t) = x(t) \quad x_\epsilon(t) = x(t) \cdot e^{\frac{2i\pi}{3}} \quad x_\epsilon^*(t) = x(t) \cdot e^{-\frac{2i\pi}{3}}$$

• Response $y$ is measured at each excitation $x$:

$$y_E(t) \quad y_\epsilon(t) \quad y_\epsilon^*(t)$$
Nonlinearity parameter extraction
NLTRM - experimental realization

- 3\textsuperscript{rd} order nonlinear term is extracted from the measured responses according to the formula:

\[ s_3(t) = N_3x^3(t) = \frac{y_E(t) + y_\varepsilon(t) + y_{\varepsilon^*}(t)}{3} \]

- Suppression of the original excitation \( x \) is performed by the energy calculation:

\[ E_{03} = \int |x^3(t)|^2 \, dt \quad E_3 = \int |N_3x^3(t)|^2 \, dt = N_3^2E_{03} \]

- Nonlinear parameter \( N_3 \) is obtained as:

\[ N_3 = \sqrt{\frac{E_3}{E_{03}}} \]

- Instead of multiplication basic excitation \( x(t) \) by complex coefficients a simple time shifts are realized:

\[ x'_E(t) = x(t) \]
\[ x'_\varepsilon(t) = x(t - t_\varepsilon) \]
\[ x'_{\varepsilon^*}(t) = x(t - t_{\varepsilon^*}) \]
FATIGUE TESTS of the AIRCRAFT WING FLANGES AND THEIR JOINTS WITH AE MONITORING & NLTRM – ESAM TESTING

L410 commuter aircraft

Loading “FLY” program cycles

FATIGUE TESTING PROGRAM:

Tensile cycling with more than 300,000 ”FLY” program cycles

AE monitoring – 9 transducers

NLTRM-ESAM procedure realized during test breaks:

- 8 multiplexed transducers (transmitters / receivers); 2 excitation amplitudes
- Direct excitation $x(t)$: sine pulse train $f = 150$ kHz (15 periods)
WING FLANGE TEST – EXPERIMENTAL ARRANGEMENT

- Preamplifiers with filters PAC
- DC supply unit for preampl.
- Multiplexer
- USB Oscilloscopes & AWG HS3/4
- AE analyzer DAKEL - XEDO
AE - ANN LOCALIZATION PROCEDURE
BASED ON "ARRIVAL TIME PROFILES"
INDEPENDENT ON STRUCTURE SIZE AND MATERIAL

\[ p_i = \frac{\sum_{j=1}^{N} T_i - \sum_{j=1}^{N} T_j}{\sum_{k=1}^{N} T_k - \frac{1}{N} \sum_{j=1}^{N} T_j} \]

**DEFINITION OF ARRIVAL TIME PROFILES**
FATIGUE TEST OF THE FLANGE # 2

comparison of the AE and NLTRM detection

AE SOURCES detected on "FLY"

NLTRM – CRACK LOCALIZATION

Final fracture

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FATIGUE TEST OF THE FLANGE #3
comparison of AE and NLTRM detection

NLTRM results

3 snapshots of AE activities
during fatigue progression

2 fatigue cracks formed later

Final fracture

Initial crack

FATIGUE TEST OF THE FLANGE #3
comparison of AE and NLTRM detection

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FRACTURE
POST NLTRM TESTING OF UNKNOWN AE SOURCE

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NWMS OF REINFORCED CONCRETE SAMPLES

7 transmitters / 6 receivers
2-frequency mixing: $f_1 = 45 \text{ kHz}$, $f_2 = 217 \text{ kHz}$ (multiplexed)
LOCALIZATION OF DEFECTIVE ZONES (CORRODED REINFORCEMENT INSIDE)

\[ n_1 = z_1 \cdot r(3f_1/2f_1) + z_2 \cdot r(f_2 - 3f_1) \]
\[ n_2 = r(f_2 - 3f_1) \]
NWMS LOCALIZATION OF CRACKS (surface scanning by Laser interferometer)

Cracks initiated during 4-point bending tests of slab samples #2 and #16. Crack photos (left) and their NWMS surface images.
Significant corrosion damage of aircraft structure observed due to seaside operation areas.

Corrosion tests on Al-alloy sheet samples

Material: Al Alloy (2024 equivalent) sheet with a thin surface layer of 99.5% pure Al
Microstructure: slight anisotropy (rolled material), contains precipitate particles, without defects
Methods (samples immersed in sea salt solutions)

(a) AE
(monitored in corrosion media)

(b) NWMS (measured in steady state)

Experimental setup:
- 2 transmitters + 1 receiver
- Harmonic signals of fixed frequencies $f_1$, $f_2$

PC

USB oscilloscope + generator

Preamplifier

Power amplifier

Specimen

Generator

$f_1$

$f_2$

Response
Corrosion test I / AE results

- Immersion in sea salt solutions 0.1 mol/l to 0.8 mol/l, total exposure 30 hours

- Continuous AE in less concentrated solution – uniform corrosion
- Intermittent burst AE in more concentrated solution – passivation
Corrosion test I / NWMS results

• Measurement parameters
  • $f_1 = 146.4$ kHz, 33 amplitude steps (5 – 120 Vpp)
  • $f_2 = 408.2$ kHz, fixed at 20 Vpp
  • $f_s = 10$ MHz (131,066 samples)
  • spectra averaging (5 repetitions)
Corrosion test I / NWMS results

• $|f_2 + f_1|$ dependence on $|f_1|$
• $|f_2 \pm f_1|$ normalized by signal amplitude
• correspondence with damage estimated by optical inspection

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Corrosion test II

2nd test: concentrated sea salt solution + addition of an acid

- 4 mol/l sea salt + 0.2 mol/l HCl or HNO₃
- no passivation
- specimens previously in 0.1 and 0.2 mol/l solutions
  - exposure time 18 hours
  - AE and NWMS
- +1 specimen
  - exposure time 80 hours
  - only NWMS
Corrosion test II / Results of AE

- intense acoustic emission
- shows current corrosion intensity
Corrosion test II / Sources of AE

- surface of specimens in SEM – face

growth of corrosion products

generation of gas bubbles
Corrosion test II / Sources of AE

- surface of specimens in SEM – edge

- growth of corrosion products
- generation of gas bubbles
Corrosion test II / Damage types

- uniform corrosion
- Al protective layer dissolved
- corrosion pits and “bowls”
- no intergranular corrosion
- no exfoliation
- no cracks
2 different nonlinearity sources

- different oscillatory mode due to the thickness change (55 µm loss in HCl, 32 µm in HNO₃)
- different nonlinearity (Al layer vanished in HCl, patches of undiluted Al layer in HNO₃)

\[ |f_2 + f_1| \text{ dependence on } |f_1| \]

\[ |f_2 \pm f_1| \text{ normalized by signal amplitude on signal amplitude} \]
AE source deconvolution using TR (Experimental inverse solution)

- Measured AE source displacement $u$ is given by product of the Green's function $G$ and source function $F$:

$$u(\vec{x}, t) = G(\vec{x}, \vec{x}_0; t, 0) \ast F(t)$$

- Theoretical inverse solution (deconvolution) can be simplified by assuming kinematical representation of AE source:

$$F(t) = P \cdot \varphi \cdot s(t)$$

- Detected AE signal $u$ is time reversed and rebroadcast from the position $X$ to $X_0$, where original source function $s(t)$ is reconstructed.
TR AE Source Location

\[ T_1 + t_1 = T, \quad T_2 + t_2 = T, \quad T_3 + t_3 = T \]
PEN – Test on the wing flange

AE signals received at 4 sensors

TR – reconstruction at 4 sensors

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5 PEN-TEST SOURCES (S1-S4)
4 AE TRANSDUCERS (T1-T4)

Source S1

TIME REVERSAL RECONSTRUCTION

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<th>CONCLUSIONS</th>
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<tr>
<td>- COMBINING AE WITH NEWS METHODS IN SHM SYSTEM IS HIGHLY EFFECTIVE AS BOTH METHODS ARE COMPLEMENTARY AND DAMAGE PRECURSORS ARE DISCOVERED EARLIER THAN BY OTHER NDT METHODS</td>
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<tr>
<td>- SMALL DEFECTS LIKE CRACKS AND OTHER NONLINEAR ELEMENTS IN MATERIAL ARE MANIFESTED BY NONLINEAR WAVE EFFECTS (harmonics, side-bands, ...)</td>
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<td>- MULTIPLEXING OF SIGNAL TRANSMITTERS/RECEIVERS ENABLE LOCALIZATION OF NONLINEARITY ZONES IN COMPLEX STRUCTURES</td>
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<td>- LOCALIZED AE SOURCES REGISTERED DURING FATIGUE TESTS CORRESPOND WITH DAMAGE ZONES DETECTED BY TR-NEWS (NWMS, NLTRM)</td>
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<td>- NLTRM DAMAGE ZONE LOCATION DEPENDS ON TRANSDUCER ARRAY LAY-OUT</td>
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<tr>
<td>- TIME REVERSAL PROCEDURE ALSO CAN BE USED TO PRECISE AE SOURCE LOCATION AND SIGNAL DECONVOLUTION, WHICH HELPS TO RECOGNITION OF AE SOURCES</td>
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THANK YOU FOR YOUR ATTENTION