NONLINEAR TIME REVERSAL ULTRASONIC PSEUDO-TOMOGRAPHY

Zdenek PREVOROVSKY, Josef KROFTA, David PREVOROVSKY
Institute of Thermomechanics AS CR, v.v.i
Prague, Czech Republic
zp@it.cas.cz

Abstract

Nonlinear Elastic Wave Spectroscopy (NEWS) becomes new effective method for non-destructive testing of complex structures providing high sensitivity of damage detection. The main advantage of this methodology consists in the ability to detect small defects relatively far from ultrasonic actuators and sensors. One of the most promising NEWS procedures is Nonlinear Time Reversal Acoustics (NLTRA) realizable in a lot of different ways. Common NLTRA procedure is mostly global, which means that localization of defect by this procedure can be often difficult. A modification of NLTRA is proposed in this paper, based on similar arrangement as ultrasonic tomography. Array of transducers is appropriately spaced on tested structure so that they cover the whole area with expected defects. One of transducers is transmitting direct ultrasonic signal and all remaining receive it. Arbitrary waveform generator is used to successively send back received and time-reversed (TR) signals along with another direct and phase shifted TR signals by all previously receiving individual transducers. Computer controlled switching between transmitting and receiving transducers is realized by specially designed high-voltage relay multiplexer. An effective schema of transmitting more signals from one transducer in each step is used, which substantially reduces the testing time. The matrix of reconstructed and back-received signals and their spectra is then analyzed, and nonlinear features like higher harmonics etc. are examined on all wave-paths. Cross-section of different wave-paths with the highest nonlinear features allocates a sector of probable defect occurrence. The use of designed procedure is illustrated on the aircraft wing skin panel with single fatigue crack. Applied experimental setup with array of seven transducers is described and measurement results are briefly discussed. NLTRA pseudo-tomography procedure can be used to roughly determine locations of defects.

Introduction

Wave Front Reversal or Phase Conjugation effects are studied in electromagnetic waves already twenty years. Recently started using of similar principles also in acoustic and ultrasonic fields, and so called Time Reversal Acoustics or Time Reversal Mirror has been developed as a powerful tool for several applications, e.g. in medicine, and NDT. Basic principles of TRA are relatively simple: Propagating acoustic elastic wave field, detected by the array of electro-mechanical transducers, is recorded, reversed in time and irradiated back toward the wave generating source. In linear, low attenuative media, the irradiated field is focused back on the source and almost perfectly reconstructed. In media with nonlinearities, caused by irregularities or defects, the time-reversed signals are concentrated around those nonlinearities (retro-focalization) and signal self-reconstruction is corrupted. Simply told, for perfectly linear systems holds the principle of superposition while for nonlinear systems it is not valid. These effects are used in so called NLTRA methodology for detection of small defects in a structure. NLTRA procedures are currently under development in several laboratories, namely in the frame of the European FP6 project AERONEWS[1]. Compared to other NEWS methods, NLTRA uses much lower acoustic power for excitation of nonlinear effects caused by defect presence in tested structure [2]. Different modifications of NLTRA were already applied to reveal fatigue-induced cracks in the sample of aircraft wing skin panel [3,4], which is also testing object in this paper. Various configurations of piezoelectric transducer arrays combined with the laser interferometer mounted on mechanical scanner were used in these experiments to excite and detect ultrasonic waves around the cracked region. Results obtained on damaged panels subjected to fatigue testing were compared with that on intact ones. Defect occurrence causes nonlinear effects changed also with growing excitation. Nonlinear effects were observed on frequency spectra of time-reversed signals, processed in different ways. The problem is that the simply realized procedure is mostly global and reflects more or less only presence of defects without their localization. Connection of non-contact wave sensing laser interferometer with scanning device helped determine the nonlinearity growth around the crack tip, and to localize present defect. Another possibilities of defect localization by NLTRA were suggested using numerical simulations of elastic wave propagation together with experimental results [5]. However, both NLTRA treatments are not applicable in situations where tested structural parts have not simple and flat geometry or when they are hidden, which is typical at e.g. aeronautical structures.

Another attempt to localize small fatigue crack in a wing skin panel, referred in this paper, has been done using a comparison of nonlinear parameters, evaluated on different wave paths examined by properly spaced array of transmitting and receiving transducers. We call this method as NLTRA pseudo-tomography. High-voltage multiplexer is used to switch between transmitters and receivers in the transducer array. Directional dependence of evaluated nonlinearity parameters help us to allocate zones with fatigue cracks or other nonlinearities caused by faulty riveted joints.

Tested object and experimental setup

The NLTRA pseudo-tomography procedure was tested on a wing skin panel sample supplied by the Aeronautical Research Institute in Prague (VZLU). The panel, representing lower part of real wing or commuter, consists of AlCu4Mg1 alloy sheet (1.2mm thickness, 0.4 m length) with five riveted stringers and central rib. The panel has been subjected to tensile fatigue loading, which resulted in 17 mm crack growing from the rivet hole. The panel drawing and its fixture in fatigue machine are shown in Fig.1.Another NEWS tests (2-frequency mixing TRA NEWS, etc.) were performed during the panel fatigue, as it was described e.g. in [6].

Experimental system assembled for NLTRA testing is presented in Fig.2. Seven piezoelectric transducers (s1 - s7) of DAKEL IDK-09 type were spaced on the panel in hexagonal symmetry manner. Transducer array covered also the cracked area. In the proposed procedure, all transducers serve as both ultrasonic wave transmitters and receivers. Exciting signals are produced by programmable arbitrary waveform generator (AWG), amplified by power amplifier (PA), and put into one selected transducer. Other transducers are receiving emitted waves and their signals are pre-amplified in low-noise preamplifiers with filters (20 or 60 dB, high-pass filter 20 kHz), and stored in a driving PC through the digital USB oscilloscopes (2 USB oscilloscopes Tie-Pie HS4, 12 bits, up to 50 MHz sampling rate). An essential component of the whole system is a computer driven 8-channel high voltage relay multiplexer (MUX), which allows computer-controlled switching between one transmitting and 7 receiving transducers. One of piezo-transducers is connected to the output of the PA (up to 1 kV, 150 W), while the other sensors are connected to high sensitive inputs of preamplifiers (1μV input sensitivity). Good shielding of all MUX relays ensures low cross talks between transmitting and sensing channels (-50 dB).

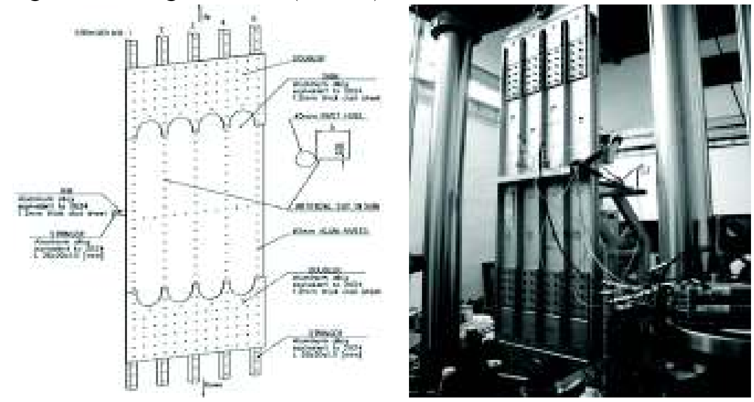


Fig.1: Riveted wing skin panel tested by NEWS procedures. Left is the panel drawing and right its fixture in a fatigue machine.

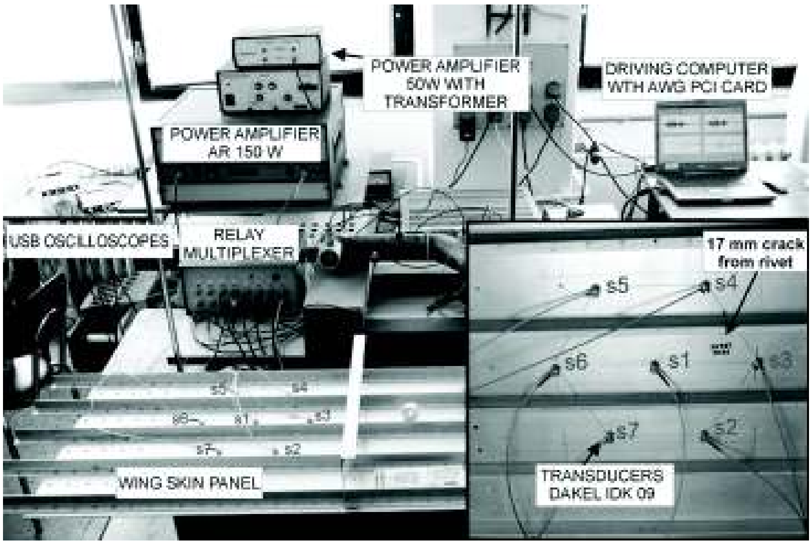
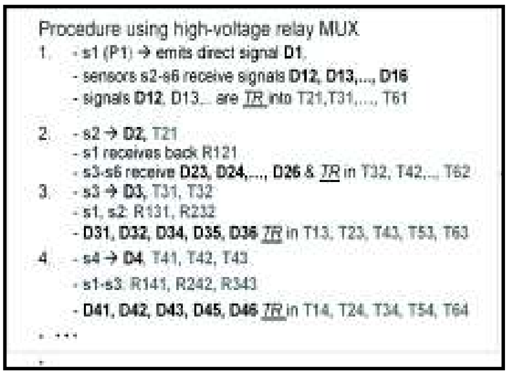


Fig.2: Experimental arrangement used in NLTRA pseudo-tomography procedure.

In the first procedure stage, a direct ultrasonic signal, created by AWG is emitted by the first selected transducer s1. A pulse train with 25 periods of sine waveform with 235 kHz frequency or other signal waveforms (Ricker pulse, chirps) was used to structure excitation. The amplitude of the excitation signal was successively increased in 2 - 10 steps ranging from $30V_{pp}$ up to approx. 300 V_{pp} at the PA output. In the second procedure stage, signal source is switched to the next transducer s2, and the series of the same direct signals with growing amplitude is transmitted along with the time-reversed (TR) and normalized signal received in previous step. A phase shifted TR signal (180^o, and/or other phase angles) is also transmitted. In the next step, a similar action is repeated with s3 transmitter, etc. Simplified diagram of the whole sequence is depicted in Fig.3 .



Procedure using high-voltage relay MUX

1. - s1 (P1) → emits direct signal **D1**
   - sensors s2-s6 receive signals **D12, D13,..., D16**
   - signals **D12**, D13... are _TR_ into T21,T31,..., T61

2. - s2 → **D2**, T21
   - s1 receives back R121
   - s3-s6 receive **D23, D24,..., D26** & _TR_ in T32, T42,.., T62
3. - s3 → **D3**, T31, T32
   - s1, s2: R131, R232
   - **D31, D32, D34, D35, D36** _TR_ in T13, T23, T43, T53, T63
4. - s4 → **D4**, T41, T42, T43
   - s1-s3: R141, R242, R343
   - **D41, D42, D43, D45, D46** _TR_ in T14, T24, T34, T54, T64

- ...

Fig. 3: Schematic outline of the successive steps in proposed NLTRA procedure.

All computer-controlled experiment along with its evaluation was programmed in MATLAB. The program control ensures automatic switching of exciting sources among the all transducer array, which allows determination of the sector containing crack, i.e. approximate damage location, providing that sensors are suitably displaced on the structure (surrounding damaged places). In some experiments, a secondary AWG with power amplifier has been used to simultaneous generation of another signals with different frequency, which enables performing another NEWS procedure - two-frequency mixing. Computer control program, allowing combination of both NEWS methods in one experimental procedure, substantially saved the testing time (approx. 15 minutes for 7 channels).

Data processing and evaluation of results.

Large amount of signals is stored into a PC memory during one test. Their number depends on the extent of transducer array; on the number of phase shifting and amplitude levels, and also on that whether we store all symmetrical components of the signal matrix (e.g. both T13 and T31 signals, which are generally not supposed to be identical). Multidimensional matrix of saved signals, containing big information about the structure geometry, material, and nonlinearities is then processed and analyzed in a lot of different ways. The simplest treatments include summation of all TR signals received back by individual sensors (linearity control of the source reconstruction), subtraction of phase-shifted signals and their sums, selective filtrations, spectral and time-frequency analysis, etc. Only few examples of tests results are presented below, and not all experimental data were processed and analyzed until now. The transmitted 235 kHz sine-wave direct signal together with initial parts of that received by other sensors in test #5 is shown in Fig. 4. The original direct signals were emitted with the amplitude at step #4 of 5 steps (148 V_{pp}). A matrix of signals received by 6 sensors from 6 other transmitting transducers is plotted in Fig.5. The matrix is not completely symmetrical as wave back-propagation conditions at both coupled transducers are not identical. On the diagonal are spurious signals of transmitting channels, plotted only for illustration of time-of-flight. These signals are induced through MUX in disconnected preamplifiers. An example of the matrix created by column sums of retroactive TR signals, received by corresponding (previously emitting) transducers in the test #4 in complete 7-transducer arrangement is illustrated in Fig.6. Well pronounced and/or multiple side-lobes are observable in some elements. These are caused by the wave propagation through riveted stringers and some nonlinearities connected with their imperfect joints. Detailed plots of

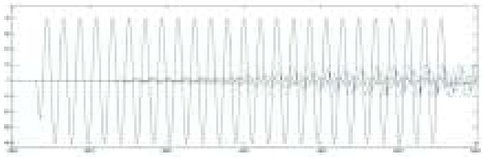


Fig. 4: Transmitted and received direct signals in the 1st stage of the procedure.

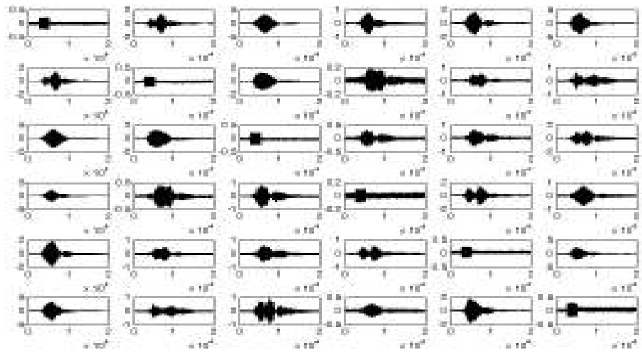


Fig. 5: Six-channel matrix of retroactive TR signals in test #3. On the diagonal are spurious copies of transmitted signals (T11, T22, ...)

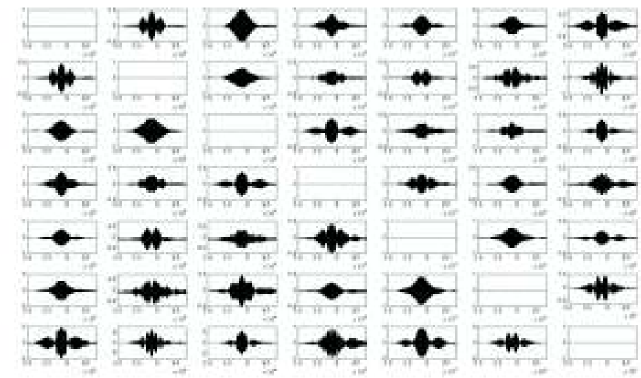
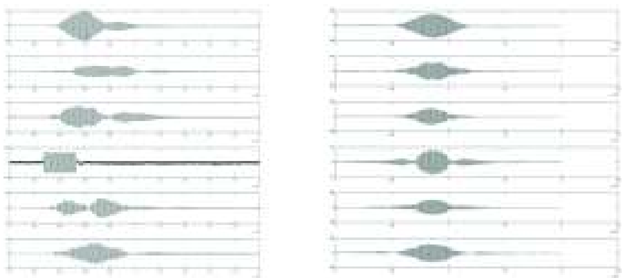


Fig.6: Matrix of retroactive signal sums in 7-transducer arrangement.



.Fig. 7: Detailed plots of signals received from transmitting transducer s4 (left) and summed retroactive TR signals returned back to all 6 channels.

signals received from transmitting transducer s4 (left) and summed retroactive TR signals returned back to all 6 channels (right) are visible in Fig. 7. Different signal waveforms reflect diverse guided wave paths from transducer s4 to the others. Summation plots in the right part show dissimilar signal reconstructions at distinct sensor positions on the panel. Two matrix plots in Fig.8 illustrate nonlinear features of the panel. In part a) is a plot of TR signals and their spectra received from s5. Two columns left represent signals and spectra obtained by subtraction of signals received at 5x higher amplitude minus lower amplitude multiplied by 5. difference in a linear case should be 0. in right columns are signals and spectra at lower amplitude. In part b) are shown signal summations and their spectra (at all channels) similarly to the previous, but subtraction is made between original and phase shifted (π) signals.

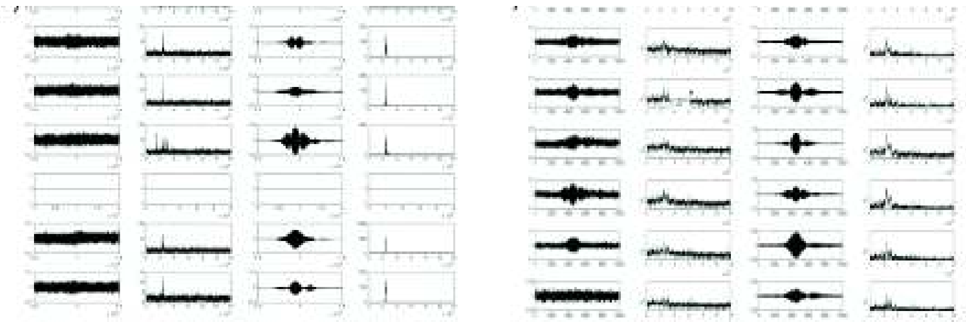


Fig. 8: a) TR Signals and their spectra received from s5 emitting two 5x different amplitudes (right are original at lower amplitude, and left are subtractions), b) Sums of TR signals and their spectra (right – original, left – subtracted originals and their π-shifted counterparts).

Conclusion

Reach possibilities of characterizing complicated structures and localize their nonlinearities caused by defects by using NLTRA pseudo-tomography method, are outlined in this paper. More detailed analysis of ultrasonic wave-path dependence of evaluated nonlinear signatures will be discussed in [7].

References

[1] K. Van Den Abeele, coordinator: AERONEWS, FP6 Project AST-CT2003- 502927 (www.kuleuven-kotrijk.be/aeronews)

[2] A. Sutin, P. Johnson, and J. Ten Cate, Development of NLTRA for Applications to Crack Detection in Solids. (Proc. of the World Congress on Ultrasonics, Sept 7-10, 2003, p. 121)

[3] S. Dos Santos, B.K. Choi, A. Sutin and A. Sarvazyan: Nonlinear imaging based on Time Reversal Acoustic Focusing. (Proc of the 8th CFA, Tours, 2006)

[4]P.Y. LeBas, K. Van Den Abeele, S. Dos Santos, T. Goursolle, O. Bou Matar,: Experimental analysis for nonlinear time reversal imaging of damaged materials. (Proc. of the 9th ECNDT, Berlin, Sept. 25-29, 2006, Th.4.6.3)

[5] A.S. Gliozzi, M.Griffa, M. Scalerandi: Efficiency of time-reversed acoustics for nonlinear damage detection in solids. (J. Acoust Soc. Am., 120 (5), Nov. 2006)

[6] Z. Prevorovsky, S. Dos Santos: Nonlinear ultrasonic spectroscopy used to crack detection in aircraft wing panel. (9th ECNDT, Berlin, Sept. 25-29, 2006, Paper No. 692; NDT-Welding Bulletin, Vol.16, No.3/2006, pp. 25-32)

[7] Z. Prevorovsky: Localization of defects in complex structures by nonlinear wave modulation and time reversal. (12th IWNEM, Ajaccio, Corsica, June 3-9, 2007, will be electronically published at ASA and AIP, November 2007)

Acknowledgements

This work was supported by the European Union in FP6 Project AERONEWS (AST-CT-2003-502927), by the Czech Ministry of Industry and Commerce through the project TANDEM (FT-TA/026-T9) of the and by the Grant Agency of the Czech Republic in grant No. 106/07/1393.