Structural Health Monitoring in aerospace and civil engineering supported with two ultrasonic NDT methods - AE and NEWS

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Abstract
Structural Health Monitoring (SHM) becomes today an important technology improving reliability and safety of aeronautical and highly stressed civil structures, and supporting their effective maintenance. Combining of two ultrasonic NDT methods - Acoustic Emission (AE) with Nonlinear Elastic Wave Spectroscopy (NEWS) - in SHM systems brings many advantages. AE enables real-time detection and localization of initiation and progression under operational stimulations, and NEWS methods provide retrieval of structural faults and complete information on AE sources. The common employment of both methods is also very effective as they both utilize the same piezoelectric transducer array, cables, amplifiers, and data acquisition devices. NEWS requires additional signal generator with power amplifier, which can be also used in AE calibration and recently also deconvolution procedures. Utilizing of common hardware reduces price of the whole SHM system. Examples of a complex SHM system design for critical parts of both aircraft and building roofs are discussed in this paper. The NEWS pseudo-tomography procedure, based on Time Reversal Mirrors (TRM) with Excitation Symmetry Analysis Method (ESAM), enabled zone-location of initiating defects, not detectable by other classical NDT procedures. Damaged zone location results corresponded with localized AE sources active within the loading of tested structures. These results reflect good robustness of both techniques, and support their helpfulness in SHM of aircraft and building structures.

Keywords: NDT, structural health monitoring, acoustic emission, nonlinear elastic wave spectroscopy, time reversal mirrors

1. Introduction - SHM systems

Structural Health Monitoring (SHM) is an emerging technology, dealing with the development and implementation of techniques and systems where monitoring, inspection, damage assessment and residual life prediction become an integral part of smart structures [1]. SHM also refers to the procedure used to assess the condition of structures so that their performance can be monitored and any damage can be detected early, thus increasing reliability, safety and efficiency of the structures. It has become an important research area in the recent past. The process of SHM involves monitoring a structure over a period of time using appropriate sensors, extracting damage sensitive features from the measurements given by the sensors and analyzing these features to determine the current state of the structure. A variety of different techniques and disciplines are merged into the SHM systems such as structural dynamics, materials and structures, fatigue and fracture, non-destructive testing and evaluation, sensors and actuators, microelectronics, signal processing and possibly structure modeling and simulations. To be effective in the development of SHM systems, a multidisciplinary approach among these disciplines is therefore required.

SHM and testing systems applied in the field may be classified as one of two general types: continuous monitoring and portable testing [2]. Long-term continuous monitoring systems collect data obtained from several parts of a structure over a long period of time (months, years). Continuous long-term monitoring require a system that can reliably operate for long periods. It is important that the system be optimized not only for high reliability but also for remote operation, eg. through the Internet connection. This requires a real time embedded subsystems that can
acquire sensor data, and periodically transmit that data to a host system. The ability of the system to operate standalone and unattended protects valuable sensor data from network interruptions. Rugged embedded subsystems must operate in harsh environments. In many cases it is necessary to just detect a deviation of the “usual” behavior of the structure, i.e. an outlier in a time-series. Automated evaluation of real state and early warning of forthcoming failure is required in SHM system. The reliability of the monitoring system is fairly enhanced combining the information obtained at different sensor nodes. Comparison of time series obtained by recording different physical quantities results in an improvement of reliability and lowers the detection threshold of deterioration. Establishment of a correlation between data and structural performance is difficult and should be based on the data interpretation expertise of the user [3].

Failures in structures can be prevented through early detection of cracks using various non-destructive testing methods. Traditional non-destructive testing methods like PT, VT, ET, MT, RT and classical UT inspection have their own limitations: they are often relatively expensive and inconclusive, cannot be fully automated and integrated into the system, and don’t bring prompt information about initiation and development of damage. Recently researchers have concentrated on nonlinear response characteristics of the cracked structures and have shown that the nonlinear behavior can be explained e.g. by models of breathing cracks [4]. Alternately, acoustic emission (AE) and Nonlinear Elastic Wave Spectroscopy (NEWS) with Time Reversal Mirrors (NEWS-TRM) methods offer an effective, fast and convenient diagnostic tool for detection of the damages in SHM systems. Both NDT methods are based on ultrasonic waves and are assumed as a substantial part of SHM system design in two currently solved research projects [5][6].

Designed complex SHM systems were tested on model parts of the aircraft structure (riveted wing flange) and building part (steel I-beam roof truss). Besides the monitoring of other structural parameters, the identical arrays of piezoelectric transducers, preamplifiers, cables, and data acquisition devices were used in both AE and NEWS method application. As AE needs stimulation of tested structure, it was monitored throughout the fatigue testing of the aircraft flange or static overloading of the building roof part. On the other hand, the NEWS procedures don’t require any loading, so they were periodically applied in the loading break intervals. Both methods revealed same damaged areas on tested model samples. Correlation of the recorded AE data with the data obtained by other methods leads to further understanding of structural behavior. Such correlation is illustrated by the use of SHM in the case of cracks formation and growth in the model aircraft wing flange fatigue test. The tested part with riveted piece of the wing skin sheet and incipient pre-crack artificially induced at one rivet hole in the central portion of sample is shown in Fig.1. Before fatigue testing, calibration measurements for both AE and NEWS-TRM method were performed to optimize piezoelectric transducer array placement and pre-set of used devices.

Fig.1: Model sample of an aircraft wing flange with riveted piece of the wing skin and artificial
Realized experimental arrangement for application both AE and NEWS-TRM methods during fatigue tests is illustrated in Fig. 2. The main components of a PC controlled device block (left) were signal preamplifiers PAC -20-40-60 independently supplied by a special 28VDC unit, relay multiplexer switching between transmitting and receiving mode of piezoelectric transducers, USB oscilloscopes Tie-Pie HS3 and HS4, arbitrary waveform generator (AWG) with power amplifier, and AE analyzer DAKEL-XEDO with parametric I/O card for fatigue test parameters recording. In the center of Fig. 2 is a photo of the tested flange with glued transducers, and detail of transducer array location is in the right part of Fig. 2. The tensile loading/unloading cycles were realized according to standard aircraft-fly testing program with inserted overloading and "landing" cycles.

Fig. 2: Experimental setup for AE monitoring combined with multiplexed NEWS-TRM pseudo-tomography (left), wing flange with attached transducers (middle) located mostly around the initial crack at rivet hole (right)

An array of 8-10 relatively wideband piezoelectric transducers (DAKEL IDK-9) was used for AE signal detection and source localization, and in NEWS-TRM for both ultrasonic wave transmitting (actuators) and receiving (sensors). An arbitrary waveform generator with power amplifier and remote amplitude control is used in NEWS-TRM to original structure excitation by 500 kHz sine waveforms, and then by their received time-reversed (TR) counterparts. Multi-channel digital signal recording (25 MHz/12 bit, 128 kSamples/channel) is realized by simultaneously triggered USB oscilloscopes and the driving PC stores all data and controls the whole procedure by program in MATLAB environment.

AE in SHM

Acoustic emission (AE) is one of the non-destructive techniques, which has an increasing use in monitoring civil and aerospace structures, and in other applications [7]. AE techniques can play a significant role for the monitoring of civil engineering and aerospace structures since they
are able to reveal hidden defects leading to structural failures long before a collapse occurs. It has the potential to detect defects during the operational service of structures. AE technique possesses several advantages over other monitoring methods, such as high sensitivity and ability to locate the damage. Damage source localization is an important part of any monitoring process. The advantage of AE method lies in the fact that the damage can be detected in real time; whereas other SHM methods such as other ultrasound based methods generally detect damage after it has occurred. AE measurement is highly efficient due to its ability to warn of crack growth. In particular, it is useful e.g. when structures exceed the designed lifetime. The analysis of AE activity and the knowledge of its changes improve the lifetime prognosis, and reduce the overall maintenance costs. Data has to be continuously transmitted (e.g. using the internet protocols) to the supervisor, where they are collected and stored in a database for subsequent analysis. This data can then be accessed by remote users. If the central unit detects a hazardous condition by analyzing the data, it should raise an alarm message. The remote unit also should allow for wireless administration, calibration and reprogramming of the sensor arrays in order to keep the whole system flexible [8].

The primary tasks of an implemented AE system networks consists of signal detection, and discrimination between noise and signals from structure deterioration. The interpretation is often limited to an indication of a “zone of interest” further investigated by other methods. New approach to AE source location on relatively complex parts has been used in our experiments. The method is based on artificial neural networks with signal arrival time profiles as network inputs. These profiles represent a new way of signal arrival time characterization, independent on material and scale changes [9]. AE source location procedure was performed remotely through the internet connection on a PC located more than 200 km apart from the AE analyzer controlled by the local PC at the fatigue testing stand. Remotely captured PC screen of distant AE analyzer controller, shown in Fig.3 displays instantaneous AE activity in 8 channels along with history of loading force (left). Right in Fig.3 are shown AE events localized during 21000 fatigue cycles. AE sources are depicted as colored points projected onto the flange photo with marked sensor positions and cracks C1-C6 revealed during and/or after the test. Unclassified AE event clusters are labeled by Sx.

Fig.3: Remote PC screen capture of a strong AE activity (osciloscopic view) -left. Localized AE
**Time reversal NEWS in SHM**

The ultrasonic wave parameters commonly used for damage detection are e.g. attenuation, reflection and mode conversion of waves due to damage. Recently developed Nonlinear Elastic Wave Spectroscopy (NEWS) methods comprise a new class of NDT techniques providing more sensitive detection and imaging of damages like microcracks, bonds weakening, corrosion, etc. The main advantage of nonlinear methods is their high sensitivity and ability to disclose defects smaller than ultrasound wavelength [10] [11].

One of the problems of employing ultrasonic waves for SHM is often their multimodal and dispersive propagation, which makes it difficult to analyze and interpret the experimental signals. Hence, a new approach is required to reduce the dispersion effects before applying signal processing techniques. One such method is the time reversal method, which enables energy focusing onto local material nonlinearities connected with defects. Recently designed NEWS pseudo-tomography procedure [12], exploiting so called Time Reversal Mirrors (TRM) with Excitation Symmetry Analysis Method (ESAM), enables zone-location of initiated defects, not detectable by the classical NDT methods. ESAM procedure [13], which uses multiple excitation to extract 3rd order nonlinearity from the ultrasonic signals, is closely related to the 3rd harmonic. It is assumed, that the crack-like defects produce odd harmonics in the acoustic response.

Time reversal (TR) can be thought of as a method that uses backward propagation of waves to focus wave energy onto a specific location in space and time [14]. TR is closely related to phase conjugation of monochromatic waves. The time-reversed pressure field, observed as a function of time, shows two wavefronts, where the second one is the exact replica of the first one, multiplied by -1. Time reversal mirror (TRM) consists of transducers array surrounding the inspected area. However, this simplification is not such a big constraint, because it can be shown that the propagation medium itself can increase the total apparent aperture of the TRM, thus resulting in a focal spot size less than the predicted by classical formulae. Moreover, a very good time-compression of resulting signals is observed in a body with multiple reflections. The properties of time-reversed ultrasonic waves can be very exploited in NDT, because a defect in a material (crack, cavity...) behave as a passive reflector. TRM defect detection is carried out using a following scheme:

1. TRM transducer array is properly displaced on the tested sample
2. TRM sends an original probing ultrasonic signal
3. The signal is reflected on the defect, so the defect thus becomes a new source
4. TRM records the reflected signal, TR signals are sent back
5. The signal is reconstructed at the original source, and defect position is located

Particularly useful is ESAM analysis as a tool which permits extraction of the nonlinear terms from direct acoustic response \( y(t) \) to excitation \( x(t) \) and evaluation of corresponding nonlinear parameters \( N_2, N_3 \):

\[
y(t) = N_4 x(t) + N_2 x^2(t) + N_3 x^3(t)
\]

(1)

\( N_2 \) and \( N_3 \) are characteristic nonlinear parameters obtained by using the properties of point group \( C_3 \). Three different excitations are used and their responses are evaluated to obtain the 3rd order nonlinear parameter \( N_3 \).

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

(2)
Three responses $y(t)$ are measured at each excitation $x(t)$:

$$y_E(t) \quad y_e(t) \quad y_{e^*}(t).$$

The $3^{rd}$ order nonlinear term is extracted from the measured responses according to the formula:

$$s_3(t) = N_3 x^3(t) = \frac{y_E(t) + y_e(t) + y_{e^*}(t)}{3}. \quad (4)$$

Suppression of the original excitation $x(t)$ is performed by the energy calculations:

$$E_{03} = \int |x^3(t)|^2 \, dt \quad E_3 = \int |N_3 x^3(t)|^2 \, dt = N_3^2 E_{03}. \quad (5)$$

Nonlinear parameter $N_3$ is obtained as:

$$N_3 = \sqrt{\frac{E_3}{E_{03}}}. \quad (6)$$

As the excitations required by the $3^{rd}$ order ESAM analysis are complex, it is not possible to use them in real experiments, since the AWG is capable to work with real signals only. Instead, two different approaches were developed to avoid the complex signals. First approach is based on amplitude variation of the input signals. Using the variation of excitation amplitude, the separation of nonlinear terms can be carried out also in spectral domain. The Fourier transform is linear, so the parameters $N_1, N_2$ and $N_3$ are not affected. As the extracted nonlinear terms still depend on the original excitation $x(t)$ and its powers (or its spectrum $X(\omega)$ with higher convolution products) a method based on energy calculation was developed to extract the values of the parameters and eliminate the excitation dependency.

Under real experimental conditions, also the higher harmonics are usually present besides other perturbations caused by the sample geometry etc. Thus the parameter $N_2$ may be considered as a signature of the even harmonics and parameter $N_3$ as a mixed signature of odd and higher even harmonics. However, these parameters can still be used for the defect evaluation, since they contain relevant information about the nonlinearity. Previous method requires precise amplitude values, which may not be feasible on most devices, therefore, another approach derived from the phase shift of the ESAM excitations was developed under assumption of sine wave train $\sin(2\pi f_0 t)$ excitation. It consists in a time shifts of $3$ excitation signals. However, the response contains also contributions of higher harmonics and other perturbations caused for example by the geometry of the sample. Instead of multiplication basic excitation $x(t)$ by complex coefficients a simple time shifts are realized:

$$x_E(t) - x(t) \quad x_e(t) - x(t) \quad x_{e^*}(t) - x(t).$$

The resulting nonlinear term $N_3$ is therefore not the pure $3^{rd}$ order term, but a mixture of nonlinear terms with suppressed linear part. Nevertheless, the parameter $N_3$ still may be used as a nonlinearity indicator.

The NEWS-TRM procedure was applied during the breaks in aircraft flange fatigue cycling. Sine pulse train with $f = 500 \text{ kHz}$ (15 periods) was used to direct excitations. Seven from
Overall 10 installed transducers were multiplexed as 1 transmitter/6 receivers in each test with different configurations. Each test was repeated with 4 different amplitudes as to optimally excite present nonlinearities. Nonlinear parameters $N_3^2$ were evaluated from ESAM TR responses along wave paths connecting transmitters with receivers. Extracted nonlinear parameters are dependent on the wave paths along damaged zones (higher when crossing area with defect), which allow pseudo-tomography imaging of defective zones. Resulting matrix of nonlinear parameters is visualized on the flange photo by ellipses along the different wave-paths between multiplexed transmitters/receivers in Fig.4 (pseudotomography imaging - left part). The width and colors (shading) of ellipses are proportional to the nonlinear parameters. Resulting image obtained by NEWS-TRM after 121000 cycles is compared with AE sources location picture shown in the right part of Fig.4.

Fig. 4: Resulting image of nonlinearities (defective zones) along wave path realized in NEWS-TRM procedure (left), compared with allocated AE sources detected during fatigue loading (right)

Fig.4 shows that results obtained with NEWS-TRM are coherent with localized AE sources detected within one precedent "fly" loading period. The most danger nonlinearity and AE event cluster are concentrated around propagation of initial artificial crack C1. These results reflect good robustness of both techniques, and support their helpfulness in SHM of aircraft structures.

**Conclusion**

Structural Health Monitoring (SHM) represents an important technology improving reliability and safety of aeronautical and highly stressed, e.g. civil structures, and supporting their effective maintenance. Incorporation of two NDT methods - AE and NEWS - into the SHM systems is highly effective, as both methods are complementary. Precursors of material damages are discovered by NEWS earlier than by other NDT methods, except AE, which requires structure
stimulation. Localized AE sources registered during fatigue loading correspond well with damage zones detected by NEWS-TRM procedure, which is applied without any stimulation.

Damage zone localization depends on transducers lay-out, so new tomography procedures with "virtual transducers" is under development. Interpretation of fatigue damage signalized by both methods becomes easier.

References
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