HEALTH MONITORING OF AIRCRAFT

BY NONLINEAR ELASTIC WAVE SPECTROSCOPY

AERONEWS

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PROJECT COORDINATOR: Prof. KOEN VAN DEN ABEELE

Deliverable D8

Description of how to provide 3D imaging of damaged regions in aircraft components using NEWS, including an estimate of the experimental accuracy

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Introduction

Improvement of NEWS techniques can lead to a significant breakthrough in the development of a new reliable and robust damage imaging system. However, extensive theoretical studies and numerical modeling are necessary preconditions to improve this methodology. To achieve such an objective, Work-Package 2 focused on the development of theoretical and numerical models to simulate damage and failure types identified in WP1 and of algorithms able to discern defective zones in large scale structures, to localize faults and to predict their impact using NEWS measurements.

The ultimate goal of WP2 is to support and suggest experimental procedures and methodologies in terms of method selection, sensor and actuator placement and data acquisition (WP1, WP3, WP4).

Two sub-packages have been distinguished in WP2: Pure and applied modeling.

WP2.1 Simulation Studies of damaged simple and complex components

WP2.2. Damage localization procedure and NEWIMAGE.

The objective for Deliverable D8 is to report – within WP2.2 – on the feasibility of the proposed imaging technique and on its possible development in order to apply it to real structures of aeronautical interest.

D8.1. A coupling between TREND and Scaling Subtraction method

D8.1.1: Introduction

Part of the scope of this project was to introduce new imaging techniques or to modify already existing (linear) ones in order to exploit the information retained by the nonlinear part of the response to a mechanical excitation of a solid structure of aeronautical interest. The importance of localize nonlinear scatterers in solid media using ultrasounds is due to the fact that a nonlinear elastic response is often the indication of the presence of microdamage and it is much more sensitive to small features than the measurement of the variations of linear elastic properties. At the same time, as also observed in many case within WP1, the nonlinear response is usually very small and hard to detect. Indeed, it easily fails within the noise level, unless transducers are localised very close to the damaged region, thus requiring consuming scanning procedure or an a-priori knowledge of the location of the nonlinear inclusion(s).
It follows that, in addition to the problems related with the nonlinearity intrinsic in the generation/acquisition system, which may contaminate the measurements, other two issues are relevant when performing nonlinear acoustic experiments.
The first concerns the illumination of the nonlinear scatterer. Being the intensity of the nonlinear response dependent on the amplitude of the local excitation, it is necessary to focus a large elastic energy onto the scatterer location. Large amplitude transducers can be used to this purpose, which generate high elastic energies everywhere in the specimen. This approach, useful in the case of distributed nonlinearities, may not be the optimal choice in the case of localised nonlinearities and for aeronautical scopes. Time Reversal Acoustics (TRA) can provide an optimal alternative, since it allows narrow focusing of energy in time and space. Recently it has been shown how a Single Channel Time Reversal can produce focusing of energy on a nonlinear scatterer: this technique is called TREND-TRA.
The second issue of interest here concerns the detection of the nonlinear signatures in the response recorded at the receivers. To distinguish between a nonlinear response (indicating that the specimen under investigation is damaged) and a linear one (indicating that it is intact), a “reference” signal is needed, which is always hard to define in practice. To this purpose, some considerations can be exploited to define an approximate “reference” signal. The most commonly used is the fact that, if the material is excited at a frequency ω_0, the linear response contains only the same frequency encoded in the excitation. Therefore, the contributions to the signal at different frequencies (higher order harmonics) are due to the presence of nonlinear scatterers. Band-pass filtering the recorded signal to cancel contributions at the excitation frequency is equivalent to subtract an approximate “reference” signal.
Nevertheless, this approaches are not always working satisfactorily in practice, since the signal resulting after a band-pass filtering is usually very small, as mentioned. In fact, most of the energy remains at the same frequency as that of the excitation. Indeed, most of the effects of the nonlinearity of the scatterer must be found on the component at the same frequency of the excitation. In fact, it is well known that nonlinear attenuation, i.e.

the dependence of the Q-factor on the amplitude of the excitation, is much more sensitive to nonlinear features than the generation of harmonics or the dependence of the elastic properties from the excitation amplitude itself. But also, conversion of energy from ω_0 to higher frequencies is expected to take place, resulting in a further effect on the dominant frequency.

In Deliverable D6, we have proposed a Scaling Subtraction method (SSM), which allows to define a “reference” signal in order to include the detection of such effects to characterise the nonlinear response. In such approach, we use a very low amplitude excitation as a comparison signal which, linearly rescaled in amplitude, is subtracted from the signal recorded at larger amplitudes to yield the nonlinear signature. We have shown that a significant improvement in the signal-to-noise ratio is obtained, both theoretically and experimentally.

We propose here to apply the Scaling Subtraction method to a TREND experiment. The use of a Time Reversal Mirror allows us to focus elastic energy in an arbitrary position of the specimen. Therefore, it is possible to focus energy in a given point and detect the signal with a transducer. If the signal contains nonlinear contributions, a nonlinear scatterer is located in the position of the focal spot. By scanning the specimen modifying the location of the focal spot, we have obtained a good image of the defect region. However, the procedure, using a standard filtering analysis to obtain the nonlinear contributions to the signal, works well only if the transducer is localised in proximity (or exactly on) the focal spot.

In the following section we will show numerically that the Scaling Subtraction method allows to increase significantly the signal-to-noise ratio, so that the imaging procedure proposed can be applied using a fixed transducer for the detection, located far from the focal spot, with obvious advantages from an experimental point of view.

D8.1.2: The imaging and filtering procedure

As described in Deliverable D7 and D9, TR refers to a process in which a propagating wave field is reversed in time and irradiated back towards the source from which it was generated. As a result of the time reversal invariance of the wave equation, the irradiated wave field focuses on the source: an high elastic energy (large amplitude wave) can be produced in a small spatial spot (with dimension related to the wavelength), with very low excitations distributed in the other portions of the specimen.

From the practical point of view, the following steps define a typical TR experiment:

1. Illumination: a transducer is located in the position $P(x_1,y_1)$ in which focusing of elastic energy is required. The transducer injects a signal z(t) and an array of N receivers record the outputs $y_k(t)$ (k=1…N);
2. Time Reversal: each receiver time reverse the signal with a proper time window of length Δ, starting from time t_0; let us call the time reversed signals $u_k(t) = y_k(t_0+\Delta -t)$;
3. Rebroadcast: receivers, now acting as actuators, inject simultaneously the signals $u_k(t)$. We observe time compression of the temporal signal recorded by a transducer

located in P and spatial focusing close to P, i.e. distribution of elastic energy with sharp maxima in proximity of the original source location.

If the original position P can be selected arbitrarily, we can obtain selective focusing in an arbitrary point of the specimen.
We expect the wavefield obtained to be able to excite the nonlinear response of a nonlinear scatterer only if the latter is located within the spatial spot. By performing a scan of the specimen by moving the point P we demonstrate that is possible to highlight the presence of nonlinear scatterers.

From NDT purpose this technique can be used associated to a proper filtering method to localized a nonliner defect (micro-damage) in a structure. In fact, by filtering the signals after the time reversal procedure one is able to detect the intensity of the nonlinearity produced by the sample as a function of the position. It is quite obvious that the nonlinearity will be larger when the wave field focuses on the defect.

Given a pure tone excitation, the signal v(t) received in a given point is dependent on the amplitude A of the excitation and can be expressed in a very general form as:

$$v_A(t) = \sum B_n(A)\sin\left(n\omega_0 t + \varphi_n(A)\right) \qquad [3]$$

In the limit of small A the solution becomes

$$v_{A\to 0}(t) = B_{1,0}\sin(\omega_0 t + \varphi_{1,0}) \qquad [4]$$

i.e. there is no nonlinear contribution to the signal, since the energy of the wave is not sufficient to excite the nonlinearity of the material.
The same is true when the material is completely linear. In this case, the solution of Eq. 2 scales linearly with the amplitude:

$$v_A^{lin}(t) = A/A_0\ v_{A_0}(t) \qquad [6]$$

To the purpose of extracting the nonlinear contributions to the received signal $v_A(t)$, in general we need a “linear” reference signal. The latter is often hard to define in practice, but a good approximation of a linear signal at amplitude A can be obtained by using a smaller amplitude excitation. Indeed, given a very small amplitude A_0, we detect an output signal $v_{A0}(t)$ approximately in the form of Eq. [4]. We therefore expect the “reference” signal at amplitude A to be given by Eq. [6].

The nonlinear response is therefore defined as the difference:

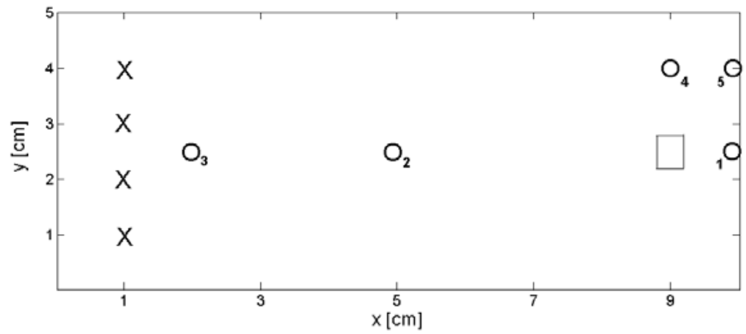


Figure 1 *: schematic representation of the virtual sample. Crosses denote the 4 transducers used for TR, the square indicates the nonlinear inclusion, while circles correspond to the receivers position (properly numbered)*

$$\mathrm{w(t)} = \mathrm{v_A(t)} - \frac{A}{A_0}\mathrm{v_{A_0}(t)}$$
$$\mathrm{w(t)} = \left(\mathrm{B}_1(A)\cos(\omega_0 t + \phi_1(A)) - \mathrm{B}_{1,0}\cos(\omega_0 t)\right) + \sum_{n=2}^{\infty} B_n(A)\sin\left(n\omega_0 t + \phi_n(A)\right) \qquad [7]$$

Evidently, Eq. [7] contains much more energy and information about the nonlinear scatterer than that contained when a simple band-pass filter is used, as in traditional methods, when the nonlinear features are identified by a filtered signal

$$\mathrm{w_F(t)} = \sum_{n=2}^{\infty} B_n(A)\sin\left(n\omega_0 t + \varphi_n(A)\right) \qquad [8]$$

Finally, we also remark that the term at the fundamental frequency in the solution of Eq. [7] can be dominant (or of the same order of magnitude) with respect to the higher order terms. As a consequence, we expect a significant improvement in the signal-to-noise ratio of the signals analysed, when we exploit the nonlinear contribution to the attenuation of the fundamental harmonic component of the detected signal.

D8.1.3: Numerical results

We have considered a 2-D specimen of dimensions 10 x 5 cm. The specimen is homogeneous, with elastic constants λ=20GPa and μ=26GPa, and density ρ=2700Kg/m^3. A low attenuation is also considered. The specimen contains a nonlinear inclusion with square shape of dimension 4 x 6 mm centred in x = 9.0 cm, y = 2.5 cm (see Fig. 1). The system is equipped with four transducers, arranged in an equally spaced vertical array at x = 1 cm. Also a set of receivers is distributed on the sample, both in proximity of the inclusion and far from it, numbered as indicated in Fig.1.
We have moved the focal point to scan the surface from x = 5.5 cm to x = 10 cm, with horizontal step of 0.5 cm and vertical step of 0.2 cm, for a result of 270 scanned points. Even though the procedure is extremely time consuming, it can be completely automatic,

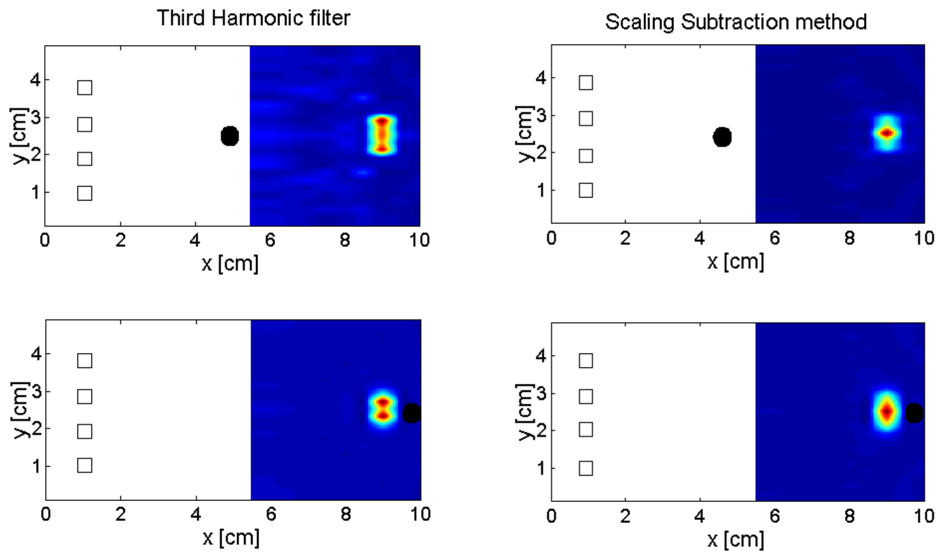


Figure 2 : *map of the nonlinear indicators $\beta_F(x,y)$ and $\beta_{SM}(x,y)$ when the focal point scans the specimen surface from x = 5.5 cm to x = 10 cm.. The quality of the image of the nonlinear scatterer is good in all cases, albeit slightly better when the Scaling Subtraction method is used.*

since transducers and receivers do not need to be moved when changing the focal spot. This is indeed the significant practical advantage with respect to the technique proposed.
A quantitative characterisation of the signals can be obtained defining a nonlinearity indicator. We choose here as a indicators the average energies of the band pass filtered and scaling subtracted signals after focal time:

$$\beta_F = \frac{1}{t_m - t_f}\int_{t_f}^{t_m} w_F^{\,2}\,dt;$$

$$\beta_{SM} = \frac{1}{t_m - t_f}\int_{t_f}^{t_m} w^{\,2}\,dt$$

Here t_f is the focal time and $t_m = t_f + nT$, where $T = 2\pi/\omega_0$ is the period and n an integer, and, as mentioned before, w_F is the band-pass filtered signal and w is the signal produced with the Scaling Subtraction method.
Therefore we can define an imaging method, based on the map of $\beta(x,y)$ obtained by scanning the surface of the specimen. In practice, we focus the back propagating field in a point (x,y) and calculate β for a signal recorded by the receiver (the corresponding value of β is assigned to the point (x,y)). Then we move to another point, etc.
The maps resulting from the simulations performed are reported in Fig.s 2 and 3. The results indicate that a satisfactory image of the defect is obtained using both band pass filtering and the Scaling Subtraction method when the amplitude of the back propagated field is large or when the receiver is close to the nonlinear scatterer: Fig. 2 and lower row

of Fig. 3. On the contrary, when the receiver is far away from the nonlinear zone, the image provided using a band pass filter is distorted or unclear when the amplitude of the back propagated signals is lower (upper left plot of Fig.3).

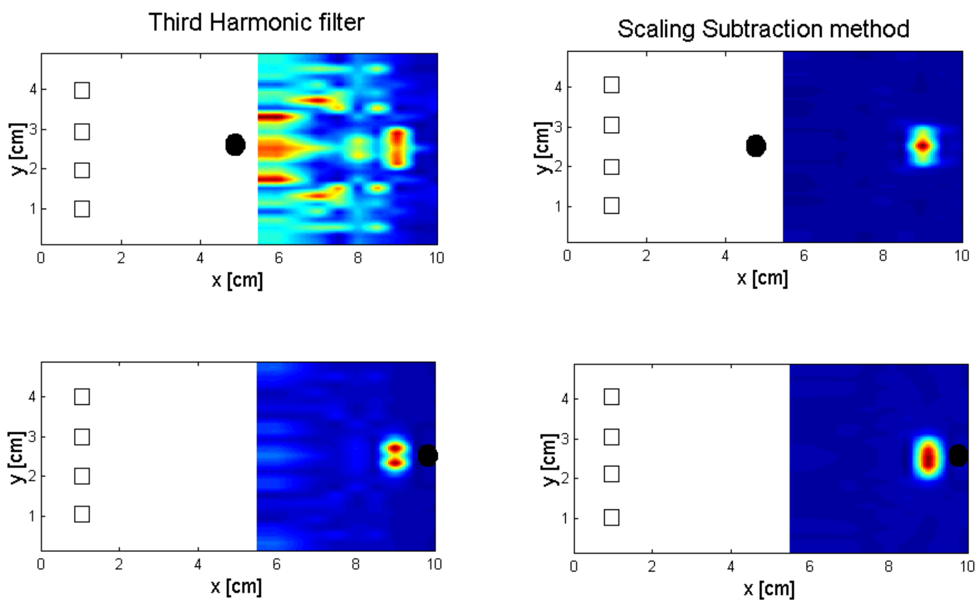


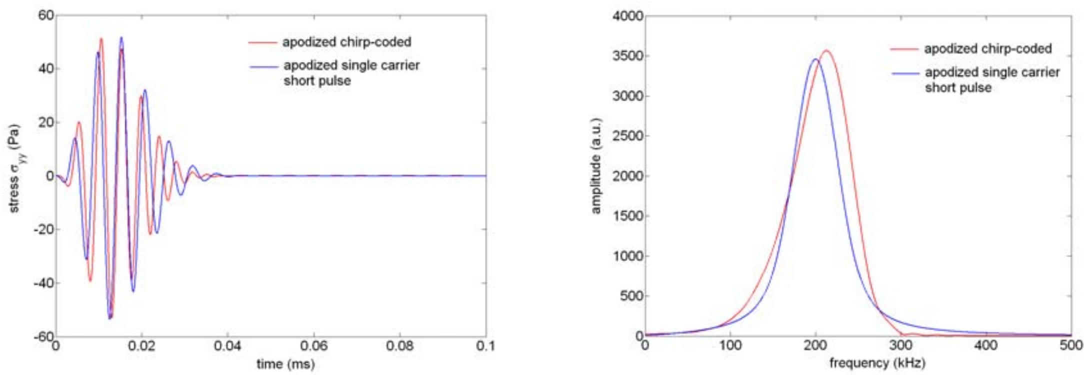
Figure 3 : *map of the nonlinear indicators $\beta_F(x,y)$ and $\beta_{SM}(x,y)$ when the focal point scans the specimen surface from x = 5.5 cm to x = 10 cm. Here we have used a lower amplitude than the case of Fig.2. The black circle denotes the position of the receiver. The quality of the image of the nonlinear scatterer is very poor when the band pass filter method is used and the receiver is located far from the nonlinear scatterer (upper left plot).*

D8.2. Chirp-coded excitation applied to NEWS-TR simulations

Time Reversal focusing improvement has been tested numerically using 2D chirp-coded excitation whose the form is defined in Eq.(1), instead of single-carrier short pulses (Figure 4).

$$e(t,x,z) = -p_0 \sin(2\pi f(t)t) \cdot e^{-\frac{1}{2}\left(\frac{t}{2/f_c}\right)^2} \cdot \left(1 - e^{-\frac{1}{2}\left(\frac{t}{3/f_c}\right)^2}\right) \cdot e^{-\frac{1}{2}\left(\frac{z-2.5}{0.15}\right)^2} \cdot e^{-\frac{1}{2}\left(\frac{x-10.5}{0.75}\right)^2} \qquad (1)$$

where $f(t) = \frac{f_{\max} - f_{\min}}{5000} * t - \frac{f_{\max} - 5001 * f_{\min}}{5000}$ with $f_{\max} = 1.7 f_c$ and $f_{\min} = 0.8 f_c$ and $f_c = 200$ kHz.



(a) (b)

Figure 4 : *(a) Temporal and (b) spectral representations of apodized chirp-coded signal(red) and apodized single carrier short pulse (blue).*

The advantage of such optimization of the excitation, also used in medical ultrasound, is its ability to transmit more energy per time without increasing the peak intensity.
The chirp-coded NEWS-TR consist in sending an apodized chirp excitation of 200 kHz of central frequency, apply the correlation function between the response of the transmitted signal on the medium and the excitation signal, and use the result as an excitation instead of the impulse response.
The obtained 2D mapping of the stress component maximum of the re-emitted time reversed signal clearly shows the retrofocusing, in this simulated linear case, of the wave at the position of the initial source (Figure 5). A similar result has been obtained with classical time reversal method, but with lower obtained maximum amplitude.

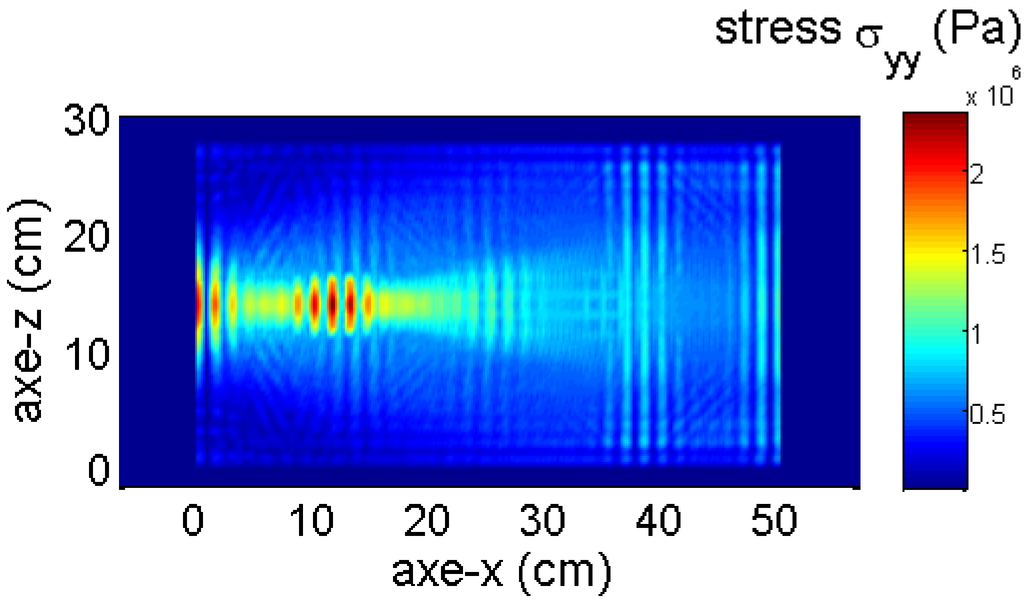


Figure 5 : *Validation of chirp-coded TR in 2D with a mapping of the stress maximum component. The retrofocusing is present at the position of the initial source (x=12, z=15).*

The aim of this study was to show the applicability of chirp-coded excitation on the time reverse and nonlinear analysis process in order to increase the stress on the retrofocused area with the TR-NEWS procedure or to increase the amplitude of the propagated signal to have more nonlinear components with the NEWS-TR process.