



**HEALTH MONITORING OF AIRCRAFT
BY NONLINEAR ELASTIC WAVE SPECTROSCOPY**

AERONEWS

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Deliverable D10

Support and guidance for experimental procedures and methodology in terms of method selection, sensor and actuator placement and data acquisition

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Introduction

Improvement of NEWS techniques can lead to a significant breakthrough in the development of new reliable and robust damage imaging systems. However, extensive theoretical studies and numerical modelling are required in order to aid the design, application and optimisation of these methodologies. To achieve these objectives, Work-Package 2 focused on (i) the development of theoretical and numerical models to simulate damage types identified in WP1, and (ii) the development of algorithms which enabled the detection of defective zones in large scale structures, localising faults and predicting their impact using NEWS measurements.

The ultimate goal of WP2 was to support experimental procedures and methodologies, providing guidance in terms of method selection, placement of sensors and actuators, and data acquisition and processing, assisting Work-Packages WP1, WP3 and WP4.

Two sub-packages were 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 D10 is to summarise the results obtained in Work Package 2 concerning the modelling support of NEWS based experimental observations and the development of a modelling supported methodology for damage localization, with reference to method selection, sensor and actuator placement and data acquisition (WP1, WP3, WP4).

This involves the following tasks:

- Identification of data to be retrieved and experimental set-up to be employed
- Optimal sensors and actuators placement according to the various level of damage typology and magnitude and tested components

Since News-TR is considered to be the best method for damage localisation, we consider in this report the Influence of test setup and specimen complexity on NEWS-TR

KU Leuven conducted a study to investigate the influence of some critical parameters on the quality of the NEWS-TR imaging methodology suggested in Deliverable D7 which is based on the combination of nonlinear harmonic filtering and time reversal. The investigation concerned information to be returned, signal length, sensor placements, and the influence of linear features such as voids and impedance barriers.

The sample under consideration is the same aluminium I-bar as described in Deliverable D7. The methodology is also identical.

Influence of the completeness of returned information

In the NEWS-TR simulations on the I-bar described in D7, all available information received at the receiver line has been used in the time-reversal process, since both the x and y components of the velocity are recorded and subsequently time-reversed. In Figure D10.1, we show the effects of including only the x or y component in the time-reversal simulation, a situation that may easily occur in realistic experimental configurations. The results are shown for two damage locations, respectively shown in the subplots (a-b) for a centrally located defect and (c-d) for a defect in the upper left corner. Plot (a) shows the effect of using only the x-velocity component in the simulation, whereas in plot (b), only the y-velocity is used.

In both cases, the wave energy readily retrofocuses at the damage zone and the time-reversal procedure remains robust. Because the wave field at the position of the defect is mainly directed horizontally, the amplitude of the retrofocused waves is stronger in (a) than in (b). In plots (c) and (d), the amplitude of the retrofocused waves is slightly higher when only the vertical information is time-reversed at the receiver. We conclude that the NEWS-TR procedure generally remains robust when only partial information on the wave field is used.

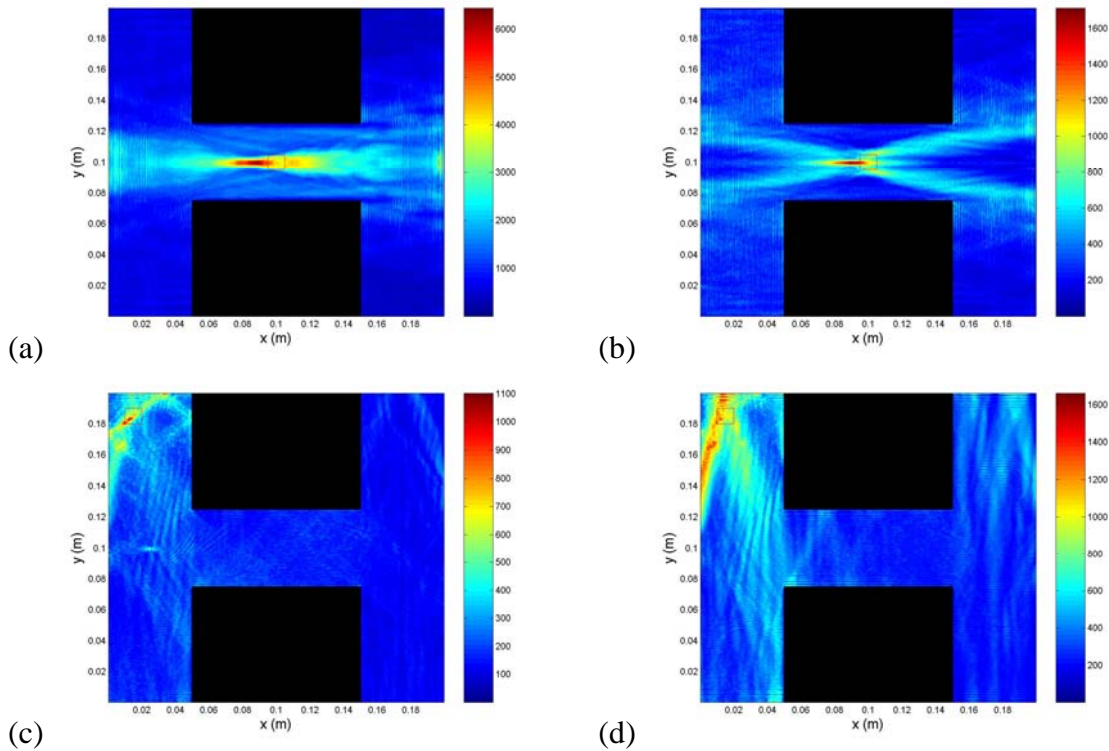


Figure D10.1: Influence of completeness of information; (a-b) damage in the centre of the section, (c-d) damage located in the upper left corner; (a) and (c) show re-injection of x -velocities only and (b) and (d) of y -velocities only.

Influence of cavities/impedance barriers

It is also of considerable interest to know whether the efficiency of NEWS-TR procedures can be significantly affected by the presence of extra complications in the structure, such as cavities and impedance barriers. We have investigated this issue with a number of specific simulations. The results are reported in Figures D10.2 and D10.3.

Figure D10.2 shows NEWS-TR simulations with a cavity added to the I-bar structure. We have performed simulations for 4 different positions of the damage zone. Both velocity components are used in the time-reversal process. We can generally observe that the NEWS-TR procedure remains quite robust, and that retrofocalisation on the damage zone remains possible despite the fact that the receiver is partially blocked by the cavity, which is located to the left of the receiver in the simulations. Depending on the location of the damage zone with respect to the cavity and the source, the cavity can block waves coming from the source to the defect, resulting in reduced efficiency of harmonic generation at the damage zone. This is particularly evident when comparing Figures D10.2a and D10.2c to the figures for the same defect positions discussed in Deliverable D7 (Figure 1b.3.11d and c). In addition, D10.2a shows that trapping of some time-reversed wave energy occurs in between the right side of the cavity and the right border of the I-bar. Waves generated at the damage zone can also be

partly blocked from reaching the receiver zone, resulting in a reduction of the amplitude of the retrofocused waves. An example is shown in Figure D10.2b, where the damage zone is close to the source, and the amplitude of the retrofocused waves is reduced compared to Figure 1b.3.11e, discussed in Deliverable D7. In Figure D10.2d, the damage zone is in the upper left corner of the I-bar and therefore this effect plays no role, but the focusing effect is slightly degraded compared to the simulation without including the cavity (see Figure 1b.3.11f, in D7), presumably because of the screening effect induced by the cavity.

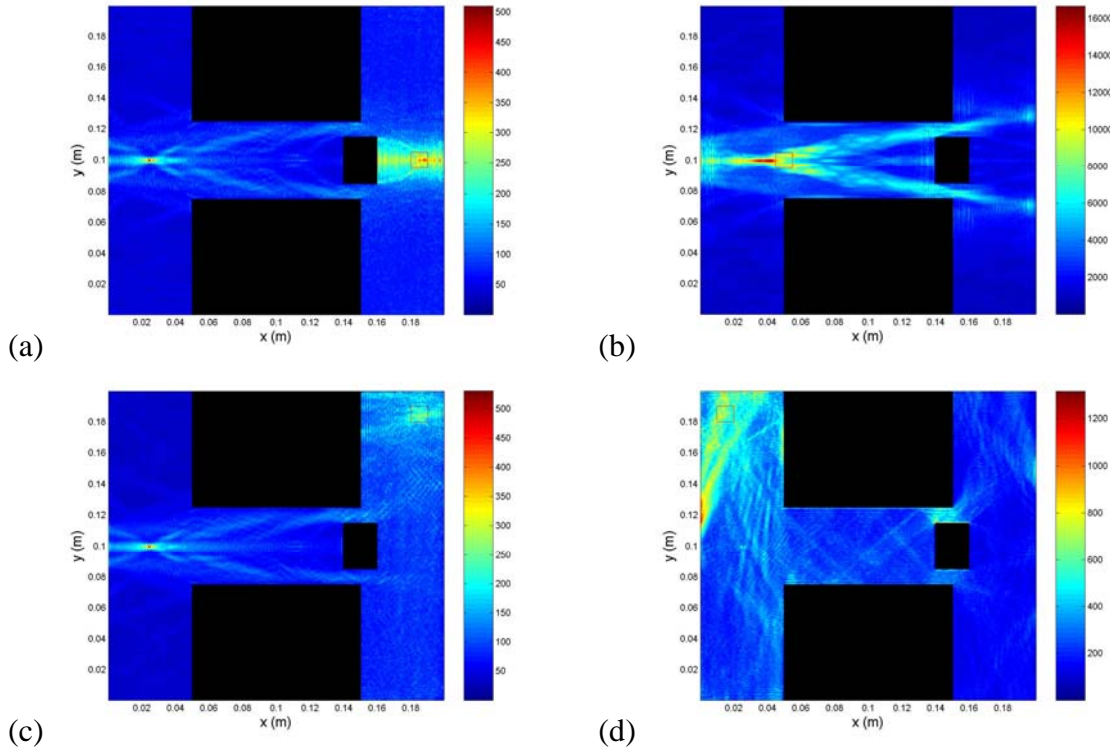


Figure D10.2: Influence of the presence of a cavity; (a) cavity between source and damage, (b) damage close to source, (c) damage in the upper right corner and (d) damage in the upper left corner.

Figure D10.3 illustrates the influence of a reduced impedance zone on the NEWS-TR procedure. The centre of this zone, which is indicated by a filled yellow rectangle in the plots, is located in between the second and third part of the I-bar and the horizontal and vertical dimensions of the zone are equal to 2 and 50 mm, respectively. Inside the reduced impedance zone, the Lamé constants and the density are divided by a factor 4 with respect to the ambient medium. The impedance barrier could for example be due to a line of glue which is used to connect the structure together. The location of the damage zones is the same as in the simulations shown in Figure D10.2. The barrier affects the time-reversal process in a much similar way as the cavity did in the previous group of simulations. In particular, Figures D10.3a and D10.3c again illustrate a reduction of the intensity of the retrofocalisation peak because waves coming from the source are partly blocked from entering the right part of the structure, whereas the amplitude of the harmonics during time-reversal is slightly reduced by the barrier in Figure D10.3b. The simulation with a defect in the upper left corner (Figure D10.3d) is only slightly affected when compared to the intact simulation (D7 Figure 1b.3.11d), although the maximum stresses are slightly higher in this case. The overall conclusion of the numerical results reported here is that NEWS-TR, at least when performed with an extensive receiver zone, can robustly handle complex structures. We may therefore conjecture that the same conclusion will hold in real experiments.

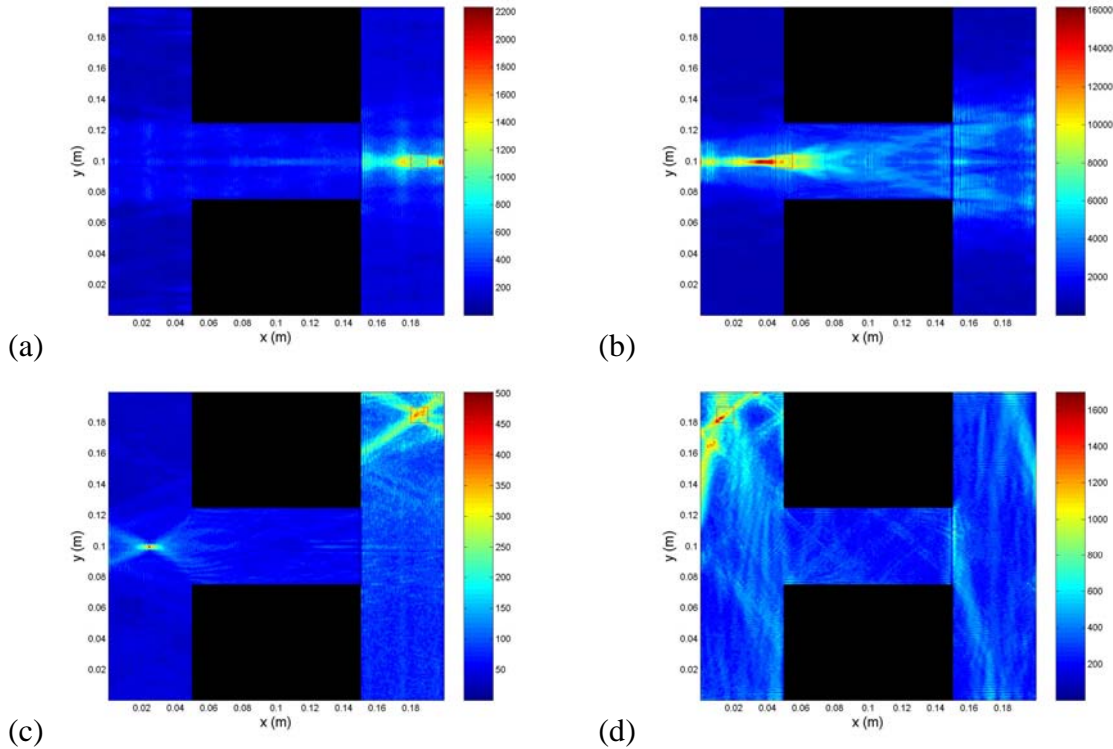


Figure D10.3: Influence of the presence of an impedance mismatch layer; the small square indicates the location of the damage.

Influence of receiver length/position

The simulations which have been reported in the previous paragraphs were performed with a receiver zone that spans almost the entire vertical height of the I-bar. With regard to the feasibility of practical application of NEWS-TR in online systems, we have to know whether the nonlinear acoustic time reversal procedure is still able to work efficiently when the spatial extent of the receiver zone is small compared to the dimensions of the structure, as happens, for example, when a small transducer is used as receiver/source. When this situation occurs, the receiver can collect only a small part of the information contained in the harmonics coming from the defect zone within a given time frame. This issue is investigated in Figure D10.4. We consider here a defect with centre located at $(x = 150 \text{ mm}, y = 115 \text{ mm})$. The vertical width of the receiver zone is reduced to 10 mm and the position of the receiver is shifted to the four corners of the sample (filled with red rectangles in plots (a) to (d)). The timescale of the simulations is kept the same as in the previous plots and both velocity components are used in the time reversal process. As expected, it is immediately evident from Figure D10.4 that the quality of the retrofocalisation degrades significantly, even to the point that the location of the damage zone can become ambiguous. The matrix plots also reveal a significant spread of the wave energy around the source and in the region containing the damage zone with only marginal retrofocalisation on the defect.

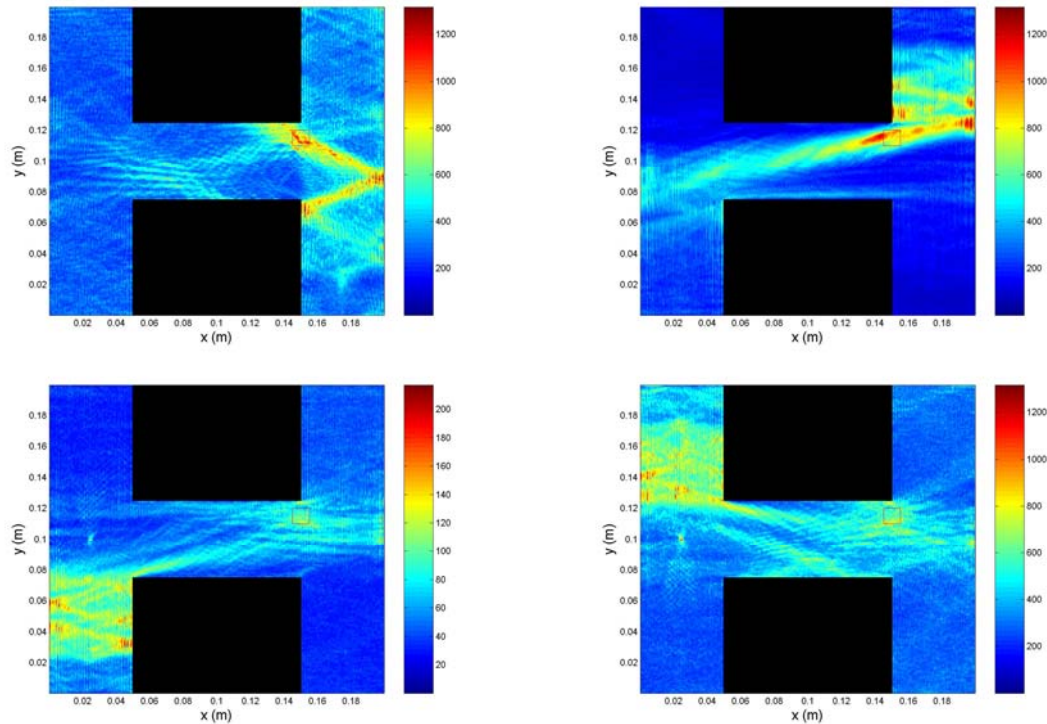


Figure D10.4: Influence of a reduction in receiver length to 10 mm; the defect is shown as a red square and the receiver as a filled red rectangle.

Figure D10.5 shows that it is fortunately possible to compensate this deficiency to a considerable extent by collecting and reemitting signals on a longer timescale. The geometry considered is the same as before, but the timescale has been increased by a factor 5. The simulations of the direct wave propagation now run over a time frame of 2 ms, whereas the time reversal runs over a period of 3 ms. A considerable improvement is immediately obvious. Only in Figure D10.5b, some degree of ambiguity still remains on the position of the defect. We have to stress that the current study does not include the effect of classical attenuation on wave propagation. The presence of attenuation will further break the time invariance of the wave equation, which only holds approximately true in nonlinear propagation problems in the first place, although we expect that attenuation will not preclude time reversal in most realistic cases.

Figure D10.6 finally illustrates two long duration simulations with the receiver zone located in the lower right corner and a damage zone in the upper left corner ($x = 15$ mm, $y = 185$ mm) including a cavity (Figure D10.6a) and an impedance barrier (Figure D10.6b) as before. In both cases, retrofocalisation occurs on the spot containing damage, further illustrating the possibility of applying NEWS-TR using small receivers by lengthening the duration of the recorded time signal.

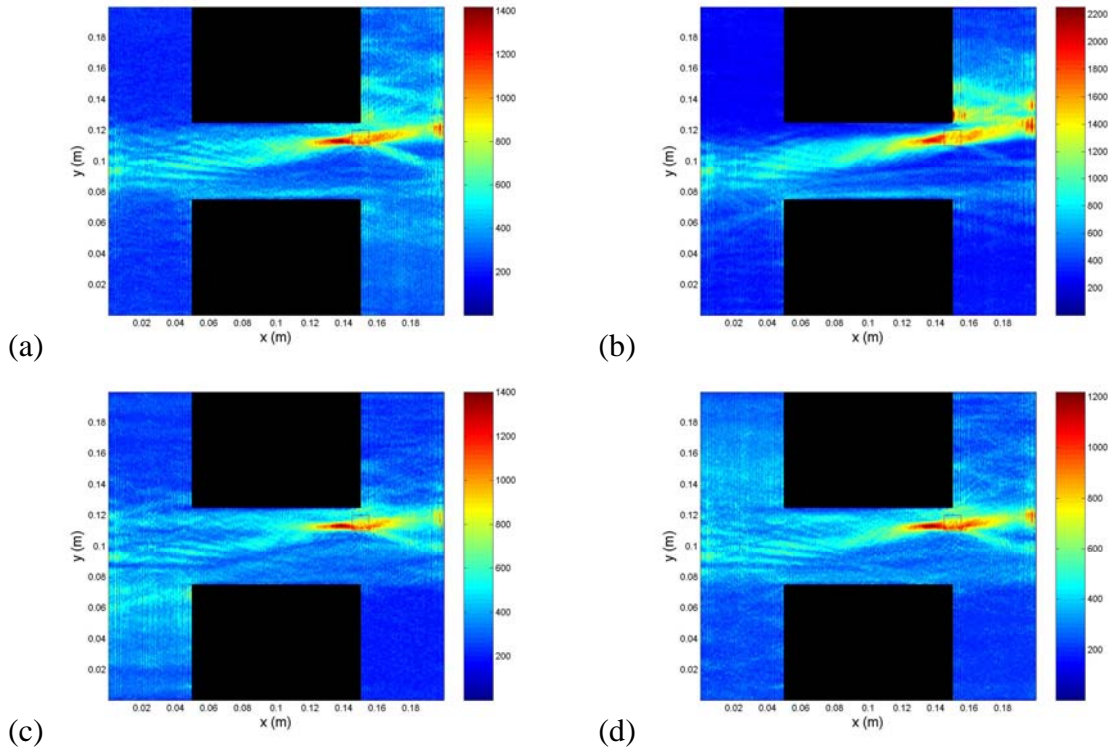


Figure D10.5: Influence of longer ($\times 5$) timescale for compensation in reduction of receiver length; the position of the receivers is the same as in Figure D10.4.

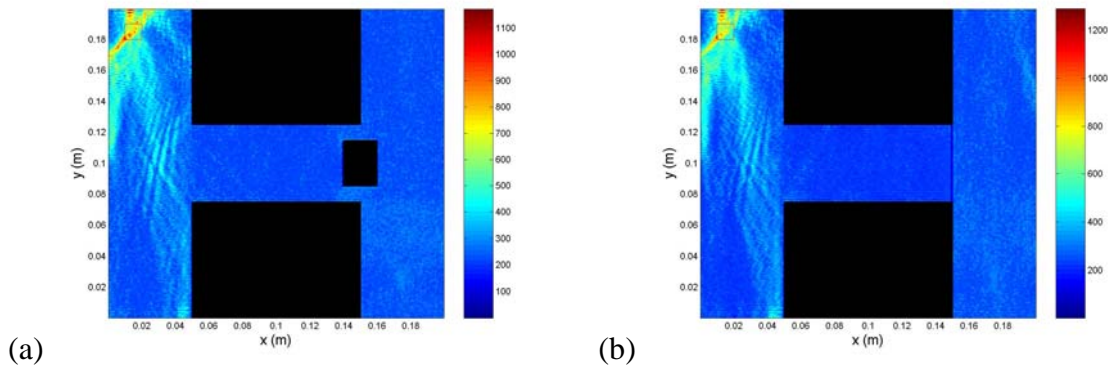


Figure D10.6: Compensation for presence of a cavity (a) and impedance mismatch layer (b) by lengthening the test timescale.