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Piezodiagnostics – damage identification via elastic wave propagation

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This paper presents a novel approach to damage identification based on the phenomenon of elastic waves propagation. The theoretical background is the dynamic Virtual Distortion Method, which is capable of modelling both a reference excitation signal propagated in the structure over a time domain and a perturbed signal due to damaged locations. The related methodology is presented including a brief description of experimental verification. Numerical example with successful identification is demonstrated. Advantages of the approach as well as its challenging points are discussed.

Key words: *damage identification, dynamic inverse analysis, elastic wave propagation.*

1. Methodology for the inverse dynamic problem

The damage detection systems based on an array of piezoelectric transducers sending and receiving strain waves have been intensively discussed by researchers recently. The signal-processing problem is the crucial point in this concept and a neural network based method is one of the most often suggested approaches to develop a numerically efficient solver for this problem.

The purpose of this paper is to propose an alternative approach to the inverse dynamic analysis problem. Generalising the so-called VDM (Virtual Distortion Method) approach for dynamic problems, a dynamic influence matrix **D** concept will be introduced. Pre-computing of the time dependent matrix **D** allows decomposition of the dynamic structural response into components caused by external excitation in undamaged structure (the linear part) and components describing perturbations caused by the internal defects (the non-linear part). As a consequence, analytical formulas for calculation of these perturbations and the corresponding gradients can be derived. The physical meaning of the so-called *virtual distortions* used in this paper are externally induced strains (non-compatible in general, e.g. caused by piezoelectric transducers, similarly to the effect of non-homogeneous heating). The compatible strains and self-equilibrated stresses are structural responses for these distortions.

Assuming possible locations of all potential defects in advance, an optimisation technique with analytically calculated gradients could be applied to solve the problem of the most probable defect location. The considered damage can affect the local stiffness as well as the mass distribution modification. It is possible to identify the position as well as intensity of several, simultaneously generated defects.

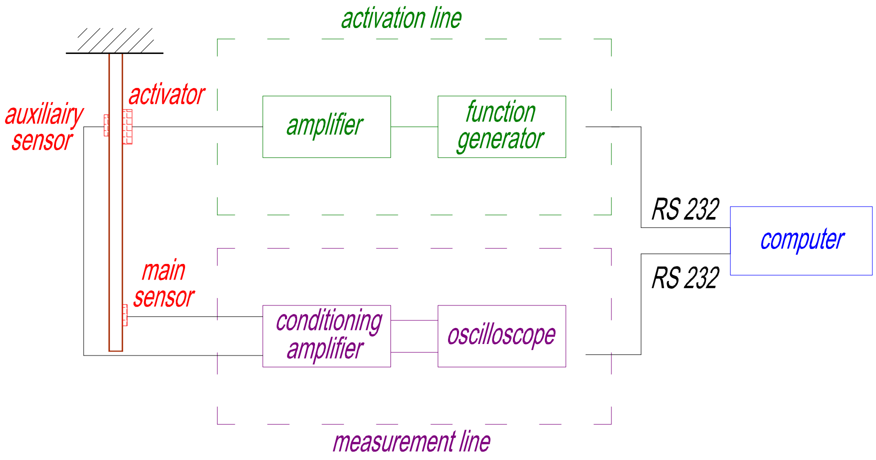

Figure 1. Scheme of experimental set-up for damage identification.

2. Damage identification system

The proposed methodology will be applied to corrosion detection (reduction of material thickness), and identification of its location in steel pipelines, using long-distance transmissions of impulses. The mechanical model can be reduced in this case to the isotropic one, with virtual distortions modelled through thermal-like, deviator-less tensor fields. This problem, similar to thermal shock propagation can be solved numerically cheaper than the general problem of elastic impulse propagation.

The proposed, time-domain-based methodology of data processing for damage identification (VDM-based *PiezoDiagnostics Software*) fits well to the following technique of measurements (*PiezoDiagnostics Hardware*):

- wave generator produces a low frequency impulse of flexural wave with long-distance propagation,
- few well located, distant sensors collect measurements of frontal section of the transferred wave,
- if the received structural response differs significantly from the reference response (for undamaged structure), the collected measurements are

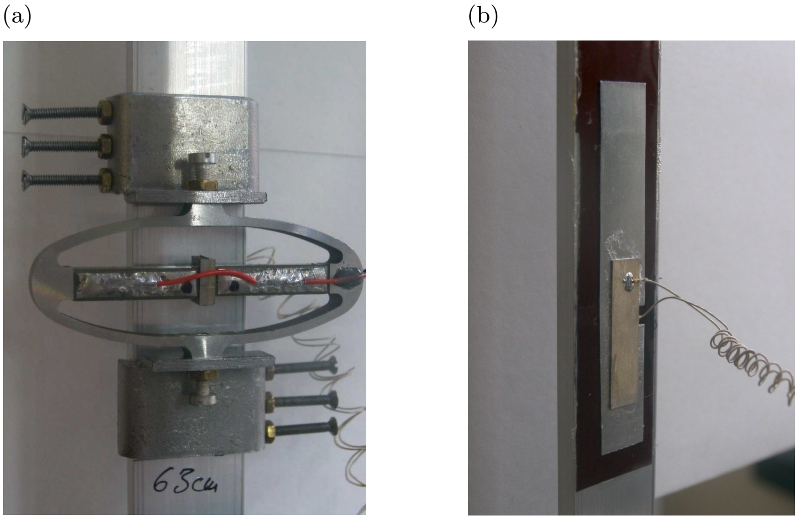

Figure 2. (a) Actuator and (b) sensor mounted on an aluminium beam specimen.

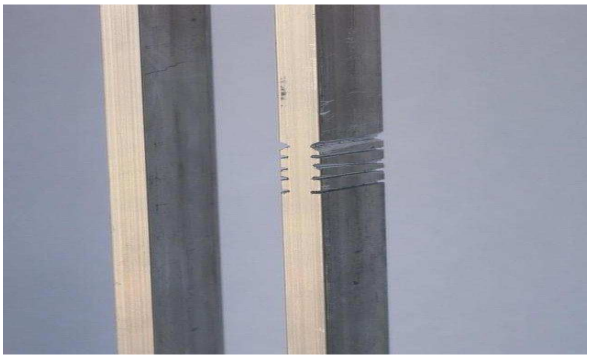

Figure 3. Original and damaged specimen (series of cuts to account for stiffness reduction).

transmitted to a computer centre for further data processing (damage identification).

The main advantage of the proposed approach is large number of measurements (done in consecutive time steps) allowing precise damage identification, including multi-damage cases.

3. Numerical example

3.1. Beam model

The objective function to be minimised (*PD Software*) describes the distance between the measured response of the damaged structure (red line with squares in Fig. 4) and the computer-simulated response influenced by the composition of all possible defects modelled by *virtual distortions* (green line with circles in Fig. 4). These virtual distortions are parameters to be identified in the efficient, gradient-based optimisation procedure, where gradients are determined analytically. Software vs. experimental verification demonstrated in Fig. 4 has been elaborated making use of a small (one meter long)

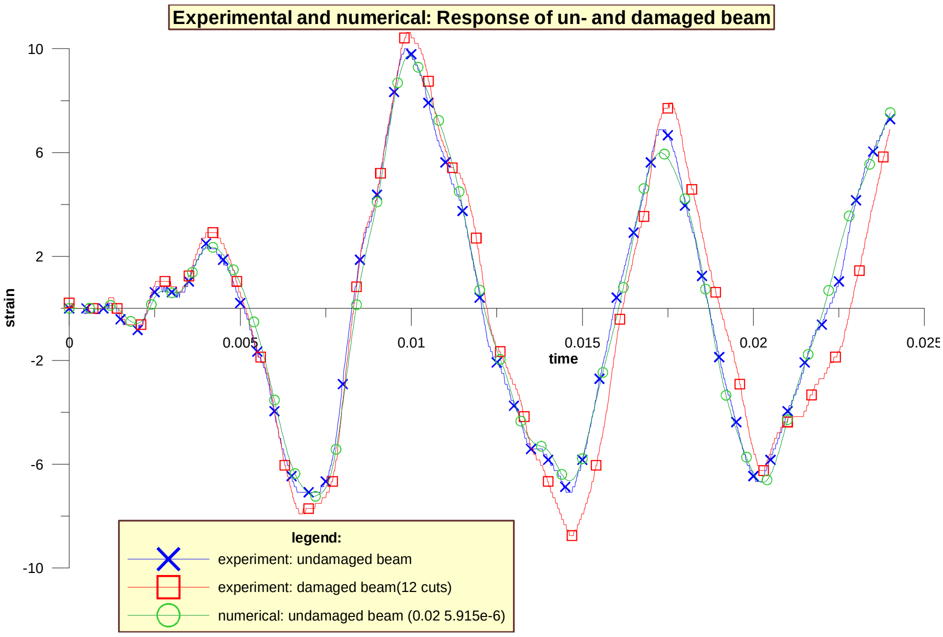

Figure 4. Numerical simulation for undamaged beam (line marked with circles) vs. measured responses for the intact (line marked with Xs) and damaged (line marked with squares) beam (1000 time steps).

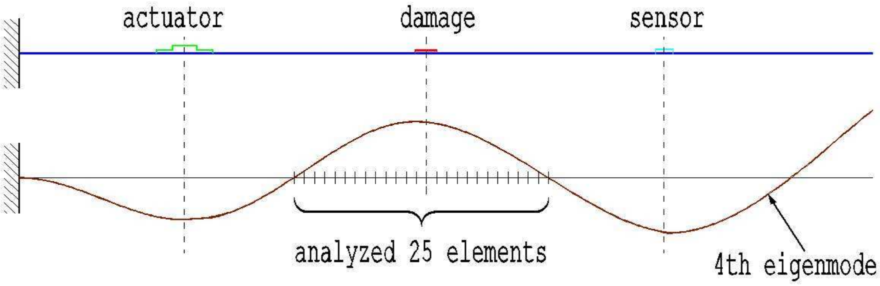

Figure 5. Beam structure with damage in the place corresponding to maximum amplitude of the 4th eigenmode.

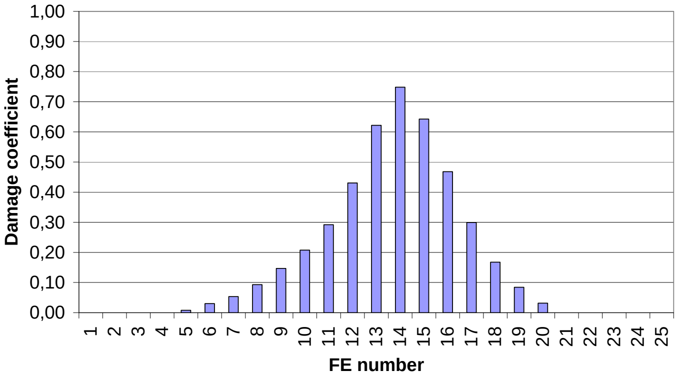

Figure 6. Damage identification results for a sine pulse excitation of the 4th eigenfrequency.

cantilever aluminium beam excited with a sine-shaped impact generated with piezo-actuator.

The VDM-based approach to damage identification consists of the following steps:

1. Assume potential locations of all possible defects.
2. Calculate the so-called *Influence Matrix* **D** describing global structural dynamic response for unit Dirac-like impulse virtual distortions generated in potential defect locations.
3. Formulate the objective functional describing *mean square-distance* between the *measured* structural response to externally generated flexural wave and the numerically composed response (superposition of undamaged structural response and linear combination of influences from all potential damages).

4. Perform gradient-based identification procedure searching for the intensities of virtual distortions (modelling potential damages) minimizing the objective functional.

3.2. Tube model

The long-term objective of the undertaken *PiezoDiagnostics* research is identification of corrosion in pipelines. Therefore a pipeline specimen shown in Fig. 7 has been chosen for subsequent laboratory tests. The piezo-driven actuator provoking long-distance elastic wave propagation in the tube is depicted in Fig. 8. A trial tuning of numerical response to experimental one is presented in Fig. 9.

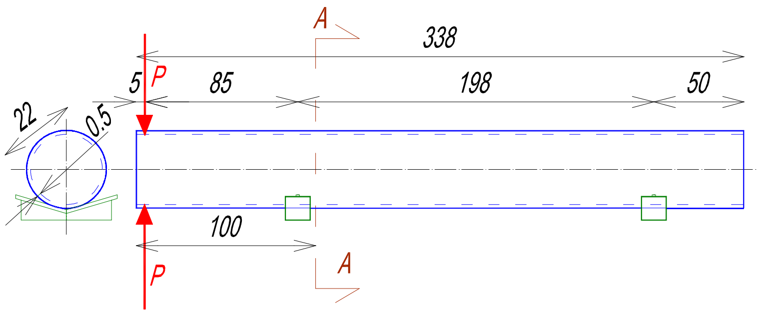

FIGURE 7. Tube specimen for lab measurements of elastic wave propagation.

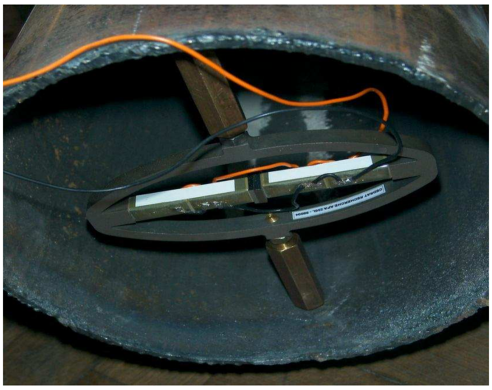

FIGURE 8. Piezo-driven actuator inside the tube specimen.

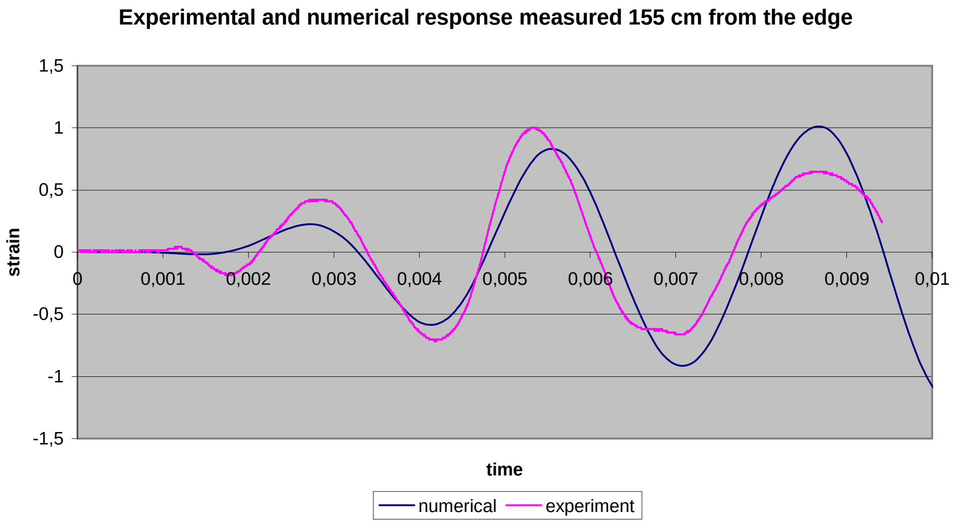

FIGURE 9. Experimental vs. numerical response for the tube specimen.

4. Conclusions

The presented new method of damage identification shows a potential to be applied in practical engineering problems. The involved dynamic inverse analysis is performed in the time domain, which makes the approach different than the commonly used frequency methods. Also building the influence matrix D provides knowledge about global-local relations in the structure, which is missing in approaches using many sensors (e.g. MEMS), distributed all over the structure, detecting response just in their vicinity. The presented method proves that few well-located sensors and the inverse analysis carried out in time (instead of frequency) domain may produce quite promising results.

The identification result obtained for the beam model is "fuzzy" – it is spread over 15 elements with the maximum intensity in the element No. 14, which corresponds to the actual defect location (see Fig. 6). The 4th eigenfrequency has been chosen for the sine pulse excitation because it gave the highest contribution to the objective function value (largest difference between the intact and damage response). Further improvement of the result can be achieved by employing e.g. other excitation signals or more sophisticated optimisation methods (steepest descent used here). However, both the structure and the considered damage (series of small cuts resulting in stiffness reduction) are of continuous character so some uncertainty of the identification result should be expected anyway.

The primary test with a tube specimen shows that a good start for matching the numerical model to experimental data has been made (see Fig. 9). Further research will be carried out and a compromise will be hopefully achieved between the accuracy of FE modelling and reliable numerical response enabling successful performance of the inverse dynamic analysis.

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