Baseline-free repetitive pump-probe experiment for structural health monitoring

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PROCEEDINGS of the
23rd International Congress on Acoustics
9 to 13 September 2019 in Aachen, Germany

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Abstract

In structural health monitoring, it is often necessary to make reference measurements on a baseline healthy sample. However, baseline parameters can be strongly affected by environmental and other conditions and significantly change over time. Here we propose a baseline-free damage localization method consisting of a repetitive pump-probe experiment in a metal plate and implementation of a back-propagation algorithm. In the reported experiment, a PZT patch generates a high-frequency (HF) probe wave at 20 kHz, while a continuous low-frequency (LF) pump of 1 Hz is produced by a shaker. Signals propagated in the plate are recorded using a set of PZT sensors glued at known positions. We use a steel ball pressed against the plate to mimic a nonlinear defect. The aim here is to produce a solid-solid contact that will be modulated by the LF pump, as would be the case, for instance, in fatigue cracks. To enhance this effect, we subtract signals recorded at different times (corresponding to different loading states) and apply the back-propagation algorithm that locates the origin of the modulation. The procedure is repeated several times to enhance the localization quality. In future, we plan to use the method with a real defect, thus exploiting more realistic contact acoustic nonlinearity.

Keywords: Imaging, Non-linear acoustics, Pump-probe, Baseline-free NDT

1 INTRODUCTION

Structural Health Monitoring (SHM) refers to a permanent inspection of a system or structure in service and includes damage detection, structural integrity assessment, as well as damage evolution prognostics and life-time estimations. Permanent monitoring should be capable of detecting fatigue damage that appears in materials under repetitive loading. Accumulated fatigue damage may lead to catastrophic consequences, especially when accompanied by environmental hazards or extreme events. A wide class of SHM systems uses ultrasound; modern ultrasonic SHM [1, 2, 3] allows one not only to detect the presence of damage but also to locate its position. In that sense, SHM is similar to imaging techniques such as ultrasonography, laser vibrometry, shearography, etc.

Many of existing SHM techniques require additional measurements on a baseline intact sample for comparison with the actual sample under study. However, even a significant difference in measured properties does not necessarily indicate the presence of damage. The matter is that materials' characteristics can slowly evolve due to aging, environmental effects, etc. In addition, measurements in the original state of a structure are frequently not available or not possible. The problem can be solved by using nonlinear methods based on strong acoustic nonlinearity induced by damage. In this case, certain nonlinear criterions should be obtained instead of a simple difference in linear properties. Hence, nonlinear SHM is baseline-free.

Modern nonlinear ultrasound damage diagnostics techniques can be divided into 2 groups: "pass-fail" tests and imaging techniques.

"Pass-fail" tests serve for detection of the presence of the nonlinear defects (such as cracks, delaminations, deboning etc.). In recent publications [4, 1, 5, 6, 3, 7, 8] "pass-fail" tests have been conducted using diversity of methods from classic reference-free nonlinear resonance and harmonic generation [6] or nonlinear wave modulation spectroscopy[1] to the late reference-based frequency mixing of coda waves with lower frequency-swept pump waves [3, 7] which is sensitive only for nonlinear defects.

As regards to the nonlinear imaging techniques providing damage localization opportunity, all of them are reference-free including nonlinear time reversed acoustic methods [1], nonlinear photoacoustic imaging [5] and break of reciprocity principle [9].

In this paper, we describe a similar imaging method based on a pump-probe experiment, in which of information of damage is provided by differences in measured HF probe signals. These differences are induced by a changing defect loading state which, in turn, is influenced by powerful LF pumping. The slight differences in HF reverberations are then used for localizing the defect. This is done by the application of the back-propagation algorithm developed in [10] for thin plates. The algorithm is based on the fact that a signal propagating in a plate following the path emitter-defect-receiver experiences certain phase transformations depending on the path length. These transformations can be compensated for by introducing an inverse phase factor corresponding to back-propagation. As a result, after a subsequent averaging over various emitter-receiver pairs a nonzero magnitude related to the emitted probe wave will be retrieved. However, if at this hypothetic defect's position (called pixel) there is actually no defect, the sum is destructive. By interrogating all pixels at the plate and by the multiple application of the back-propagation algorithm, a full image can be produced. This imaging method has been applied (see Chehami et al. [11, 12]) for linear defects such as holes or rigid inclusions and is adapted here for a model defect mimicking the behavior of a real nonlinear one. In our preliminary experiments, we use a steel ball pressed against an aluminum plate. Similarly to a crack or delamination, the ball excited by the LF pumping slightly modifies the propagation conditions for the HF probe. These weak changes are considerably enhanced by the application of the back-propagation algorithm due to multiple averaging over different loading states. In the next section, the experimental procedure and signal processing are described in greater detail. Results of imaging are presented in Section 3 followed by concluding remarks in Section 4.

2 REPETITIVE PROBING SETUP AND SIGNAL PROCESSING

In these series of experiments, the objective is to localize the origin of modulation due to a solid-solid contact (here it is a steel ball pressed against the surface of a plate) on a thin plate using ultrasound.

2.1 Experimental procedure

An aluminum rectangular plate (1 m × 0.5 m × 3 mm) is horizontally suspended with elastic cords on a metallic support. A 1 cm diameter steel ball is pressed against the top surface of the plate with elastic steel ruler fixed on the support cage (see Fig. 1).

The ball plays the role of a nonlinear defect (i.e., fatigue crack) to be localized. In order to find out the defect position, a pump-probe experiment has been conducted. One PZT patch (glued to the plate to provide acoustical coupling) generates a high-frequency (HF) probe wave which is a 100 ms burst with 1 cycle of 5 Vpp sine wave at f_{probe} = 20 kHz (see Fig. 2-(a)).

At the same time, a vibrating shaker rigidly attached to the plate and to the support cage produces a low-frequency (LF) pump wave which is a continuous 3 Vpp sine wave at f_{pump} = 1 Hz (see Fig. 2-(b)). LF shaker parameters are so as plate continuously performs vertical oscillations, in a such a way that the position of the ball and the plate-ball contact loading state (stress, displacement) slightly changes all the time. The reverberated signals are acquired at 7 PZT patches similar to the PZT emitter, using National Instrument acquisition card (500 kS/s, 8 channels). The signals are amplified at reception. The total length of the HF probe reverberated signals is 50 ms which is much less than one period of the pump wave. The acquisitions are repeated for N = 20 times while HF and LF stimulus are excited. An average time between 2 acquisitions is 50 ms. These different acquisitions correspond to different contact loading states and defect position. An example of received

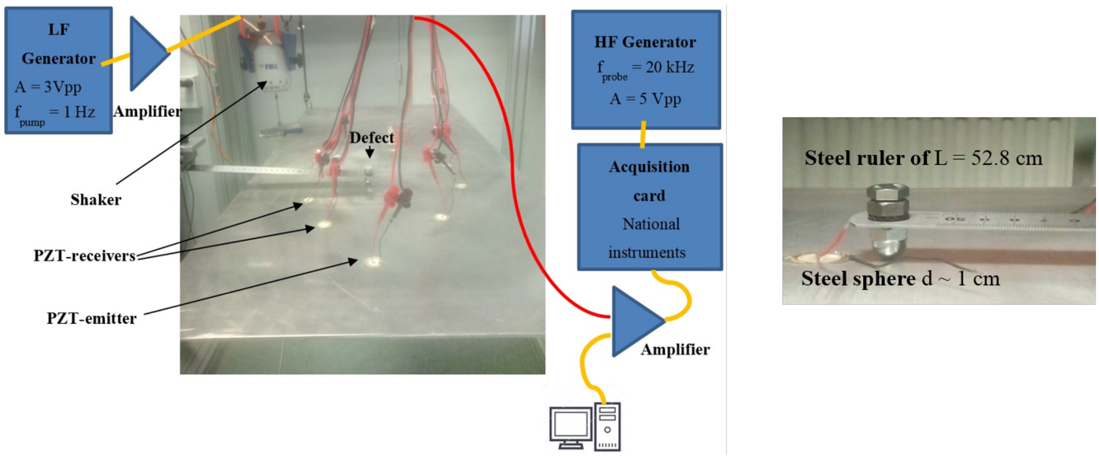

Figure 1. (left) Pump-probe experimental setup. (right) Nonlinear defect "solid-solid" contact.

exponential-decayed signal is shown in Fig. 3.

The idea of these different acquisitions is to collect as much data (information) as possible for different defect state without removing the defect. Elastic rubber cords attaching shaker to the support cage makes the shaker "invisible" in the resulting images (shaker-plate contact assumed to be negligible).

2.2 Signal processing: back-propagation algorithm adapted to repetitive probing experiment

Let us denote by s_m^j $(j = 1...N_T)$ the m^{th} acquired signal at known receiver position r_j, N_T is number of receiving transducers. To enhance the effect of modulation, one should make subtractions between signals at different loading states, i.e., $s_{m+1}^j - s_m^j$ $(m = 1...N$ acquisitions). We obtain then the subtractive matrix denoted by Δs_m. We note that for N acquisitions there are $N_s = (N^2 - N)/2$ possible subtractions.

The second step is discretizing the given structure in a mesh grid with a given spatial step $\Delta x = \Delta y$. Then one should compensate wave phase shift due to wave propagation via point (x,y) (pixel). The principle is to take the element of index j of Δs_m matrix and back-propagate it according to the current pixel position (x,y). The back-propagation function (bpf) of Δs_m is estimated from Eq. (1):

$$bpf_{(x,y)}^{m}(\omega) = \sum_{j=1}^{N_T} \Delta s_m^j(\omega)\, e^{ik(\omega)\, r_{Ej}(x,y)}, \tag{1}$$

here $r_{Ej}(x,y)$ is the distance between the emitter E and the jth receiver via the pixel at position (x,y). The wavenumber k obeys to the dispersion relation of A0 Lamb mode (flexural wave). Matrix element $\Delta s_m^j(\omega)$ is the Fourier transform of $\Delta s_m^j(t)$. Only the time interval that includes the direct propagation between the defect and the receivers is kept. In practice, due to the electronic setup, the response of the transducer toward itself cannot be measured. For this reason, the element$\Delta s_m^{EE}(\omega)$ is not considered to compute bpf.

To obtain the scattered energy in each pixel for a certain subtraction one should go back to the time domain through an inverse Fourier transform, the pixel energy at position (x,y) is then obtained by integrating the back-propagation function over time T_0 (accordingly to the approximation of back-propagation in an infinite plate), i.e.,

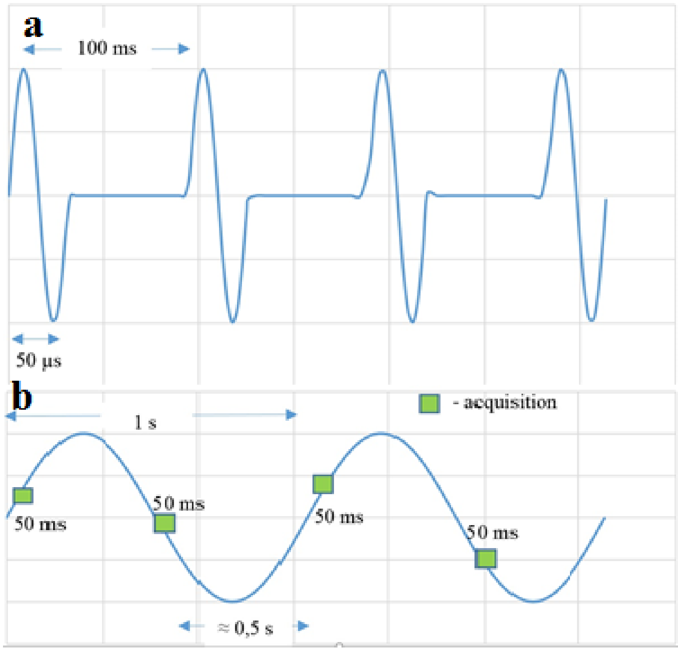

Figure 2. Typical signals: a) HF probe provided with PZT patch at 20 kHz, and b) LF pump provided with shaker at 1 Hz.

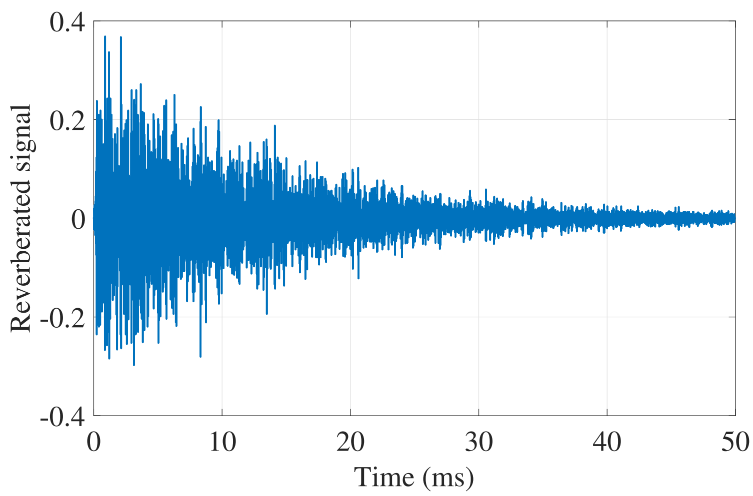

Figure 3. Example of received reverberated signal on one PZT.

$$E_m(x,y) = \int_{-T_0/2}^{T_0/2} \left| bpf^m_{(x,y)}(t) \right|^2 \mathrm{d}t, \tag{2}$$

where T_0 is typically the inverse of the bandwidth. For pixels located on the defect, this process will be equivalent to a numerical back-propagation of the signals to zero time (instant of the emission) followed by a coherent summation of the back-propagated signals. This will lead to a constructive sum and a local maximum of the pixel energy is obtained as shown on Fig. 4-(top). For pixels located elsewhere, the obtained energy will be made up of a summation of non-coherent contributions corresponding to the reverberations at the plate boundaries as shown on Fig. 4-(bottom).

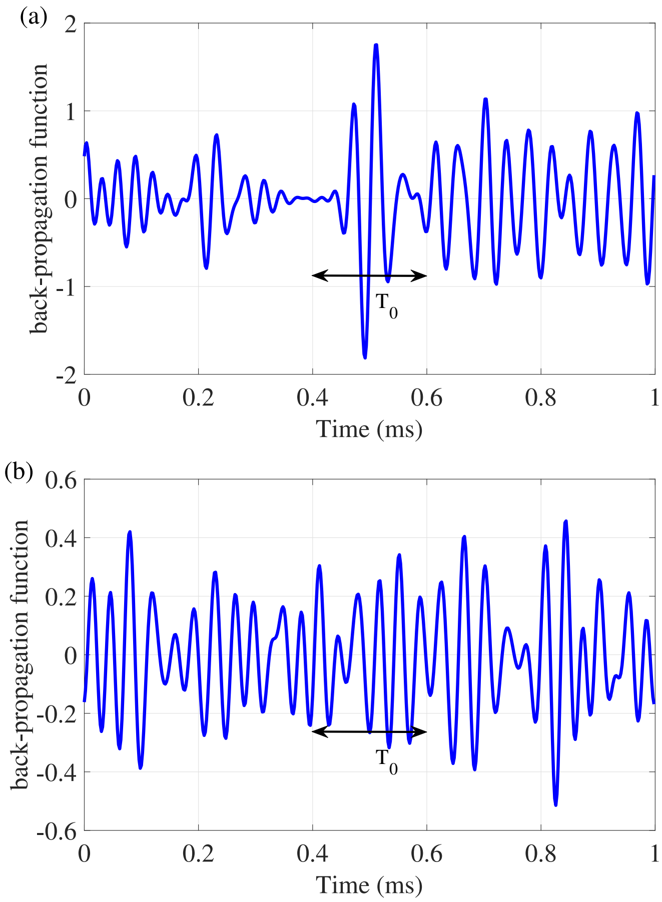

Figure 4. Example of back-propagation functions when pixel (x,y) is: (a) on the defect position, and (b) elsewhere.

Finally, we get the cumulated energy by averaging Eq. (2) over all N_s subtractions (i.e., all the pairs of loading states):

$$E(x,y) = \frac{\sum_{N_s} E_{mn}(x,y)}{N_s}. \quad (3)$$

Localization results are shown and discussed in next section.

3 RESULTS AND DISCUSSION

The obtained results are shown on Fig. 5. The positions of transducers are indicated by crosses and that of the shaker and defect by, respectively, a circle and a square. The origin of coordinates is taken at the left lower corner of the plate. The spatial pixel resolution is Δx = Δy= 5 mm. One of the transducers array is used as emitter for each figure.

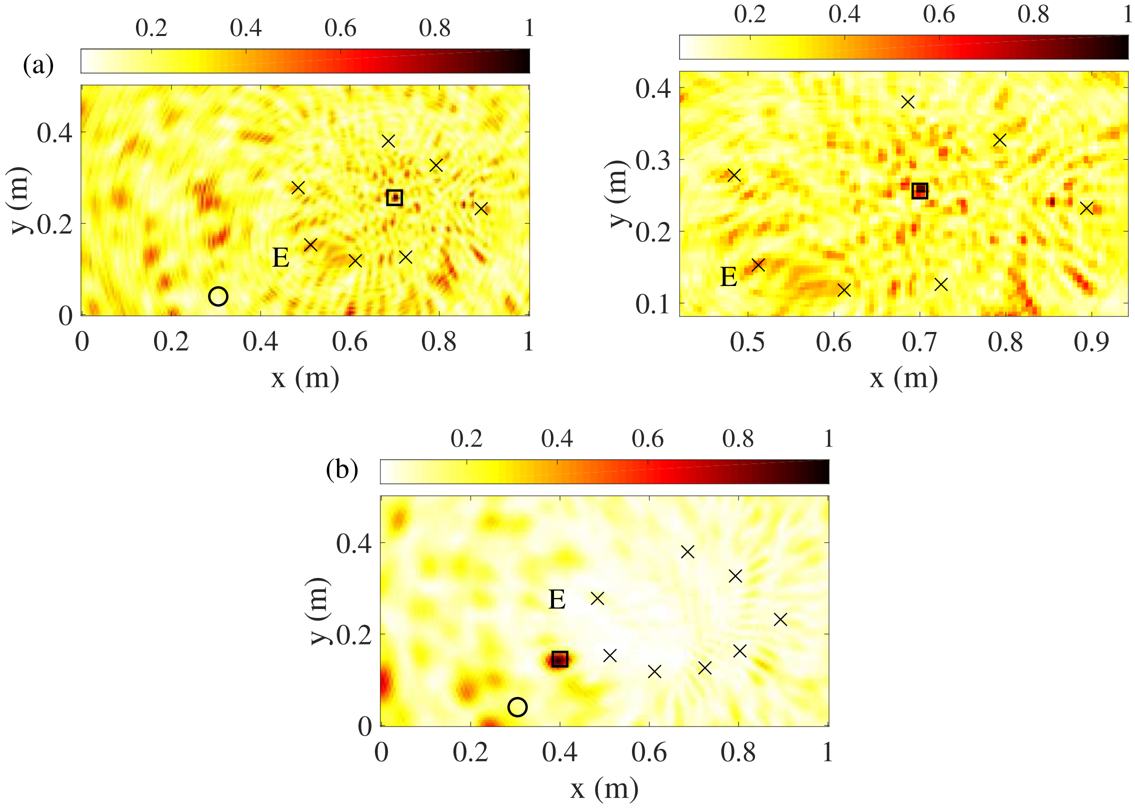

Figure 5. Imaging localization results obtained for a nonlinear solid-solid contact located at: (a) [0.695,0.264] m, and (b) [0.4,0.145] m. (a-right) Zoom on the receivers area. The positions of the shaker and defect are, respectively, indicated by a circle and a square. *E* is the emitter.

On the obtained images we can see that it is possible to localize defect inside and outside the transducers area. In comparison with the results of a conventional back-propagation algorithm applied for baseline experiments (see L. Chehami et al., [10]), in the current images signal-noise-ratio (SNR) is lower: there are many artifacts. This can be interpreted by the lack of information about the modulation effects: in contrast to the array of emitters used for baseline experiments, in pump-probing experiments only one transducer plays role of emitter. Consequently, there are some preferred directions, mutual location of emitter, receivers and defect matters. Finally, we should mention that some problems can occur if during the experiment acoustic emission (squealing) appears.

4 CONCLUSIONS

Here we proposed a baseline-free repetitive pump-probe experimental procedure to detect a contact-like nonlinear defect. The localization of the origin of modulation based on adapted back-propagation algorithm has been described. Efficiency of the algorithm has been illustrated with localization of a 1 cm steel ball pressed against vertically oscillating aluminum plate. Imprecision of this algorithm is connected with an asymmetry of transducers geometry (only one of them plays the role of emitter), in contrary to conventional beamforming algorithm, where all the transducers are at the same time both emitters and receivers. Thus, in this configuration there are preferred directions, and a success of defect localization depends on mutual location of defect and transducers. Consequently, there is also dependency on the choice of emitter. For the optimized emitter and parameters of both pump and probe waves, defect can be successfully localized without an hypothetical reference (without damage).

These preliminary results are very encouraging for SHM, especially for nonlinear acoustics. Future works will be focused on the improvement of the SNR images and adapting the current algorithm for passive SHM, without need of ultrasonic emitter.

ACKNOWLEDGEMENTS

This work has been supported by the French National Research Agency (ANR). Grant number ANR-17-CE08-0013-01 (PANSCAN project).

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