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Non destructive auscultation and imaging of damages by distributed sensor array: step towards passive SHM under real conditions

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Abstract. The passive imaging based on the Green's functions reconstruction from ambient noise correlation became a promising technique in structural health monitoring. Here, this approach is used to detect and locate linear defects (cracks, holes...) in thin reverberant plates with a small number of sensors. Correlation matrices before and after defect occurrence are estimated from friction noise. Based on a dispersive backpropagation algorithm in a thin plate, the differential matrix of correlations (before and after defect) is used for defect localization. This technique shows satisfactory results for linear defects, but refers to a measurement on a baseline healthy sample, which can be strongly affected by environmental conditions. In this context, an active baseline-free damage localization method that uses a repetitive pump-probe experiment, is proposed. A series of experiments are conducted in a thin aluminum plate using 7 PZTs sensors glued at known positions. One transducer generates a high frequency probe wave with central frequency 20 kHz, while a continuous low frequency pump of 1 Hz is produced by a shaker. A steel ball pressed against the plate to mimic a nonlinear defect is considered. The aim here is to produce solid-solid contact that will be modulated by the pump wave, as would be the case for instance in fatigue cracks. In order to enhance this effect, signals recorded at different times (corresponding to different loading states of the contact) are subtracted and back-propagated to locate the origin of the modulation.

Keywords: Noise Correlation · Beamforming · Pump-Probe.

1 Introduction

Twenty years ago, Weaver and Lobkis proposed a new way to exploit and take benefit from noise sources. The authors have experimentally shown on an aluminum block that the cross-correlation of elastic noise between two receivers provide the transient response between the two receiver positions as if one of them acted as an elastic transient source, interpreted as the Green's function GF of the medium [1]. Actually, this property is not limited to thermal noise source but to any noise source distribution that generates an equipartitioned wave-field. In fact, in some situations it is desirable to avoid the need of active energy sources. So, the major interest of this result is the estimation of the GF without requiring any energy source. The main application of the Green's function extraction from noise correlation function (NCF) is in seismology where Artman has demonstrated the universal interest [2]. Passive Green's function estimation also offers promising applications in other domains ranging from ultrasound [3], underwater acoustics [4,5] to medical imaging [6].

In ultrasound applications, and particularly in structural health monitoring field, power consumption and complexity of the electronics might represent key issues for the standard methods used in active configurations (pitch-catch). An alternative way could then consist in taking benefit of ambient noise to reveal defects (cracks, holes, etc) by passively estimating the GF using the physical principle based on noise correlation approach. Only a few works are devoted to structural health monitoring. In this field, a pioneer work consisted to use the traffic excitation to recover resonant frequencies and modal damping of a bridge from noise cross-correlation [7]. Later, this approach have been applied to extract the Rayleigh-Lamb Green's transient responses on plates [8,9]. The method is sufficiently sensitive to observe elastic signature of a plate defect on the cross-correlation [8]. To localize a defect, an original method has been proposed [10] that is particularly efficient when noise sources distribution is not uniform. The possibility of detecting and localizing defects using ambient noise (friction noise, acoustic noise...) more or less uniformly generated on surface plates has been recently demonstrated in recent works: numerically [11] and experimentally [11,12,13]. Some studies on the defect characterization are also derived based on the estimation of the far field pattern called scattering cross-section" [14]. A statistical approach was also proposed by Chehami et al. [15], which relates the similarity between the cross-correlation and the GF to the structural properties of the plate and the number of uncorrelated sources.

Based on all these studies, suitable noise sources for passive imaging application should be uncorrelated, spatially stationary and with wide-band frequency contents in the ultrasound range. This technique shows satisfactory results for linear defects, but requires additional measurements on a baseline intact sample for comparison with the actual one. The matter is that material's 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 [16]. In this case, certain nonlinear criterion should be obtained instead of a simple difference in linear properties. In this context, an active baseline-free damage localization method that uses a repetitive pump-probe experiment, is proposed here.

The paper is organized as follows. In Section 2, we study the passive defect localization tested for holes, massive inclusions or even cracks. In Section 3 the baseline free-method base on pump-probe experiment is proposed and tested in mimic defects similarly to a crack or delaminations. Results of localization and imaging are presented and followed by concluding remarks in Section 4.

2 Passive defect imaging

A reverberating plate with a set of transducers fixed on its surface and subject to ambient acoustic noise is considered. It has been shown in a recent work [11] that the differential correlation matrix, that is obtained from the subtraction of the correlation matrices with and without defect, is given by

$$\Delta\mathbf{C}(t) = [\Delta\mathbf{G}(t) - \Delta\mathbf{G}(-t)] \otimes f(t) + \Delta\mathbf{n}(t), \tag{1}$$

where $\Delta\mathbf{G}$ is the part of the Green's function due to the defect and $\Delta\mathbf{n}$ the correlation residue (or reconstruction error), depending on the number and the distribution of noise sources. Function $f(t)$ can be considered as a virtual excitation waveform and is given by

$$f(t) = \frac{N_S \tau_a}{2\mathcal{S}\rho h} \int_{-\infty}^{t} R_n(\tau)\, d\tau, \tag{2}$$

with N_s is the number of sources, h the plate thickness, ρ the volume density, $\mathcal{S}$ the plate area, $R_n(\tau)$ the autocorrelation of the noise source and τ_a the characteristic attenuation time constant of the plate.

As shown in previous works [11,12], this differential correlation matrix can be used as the input of a defect localization algorithm, as though it was an actively acquired signal matrix. However, two conditions are necessary for efficient detection: first the noise should have non-negligible components in the useful frequency band (where wavelengths are of the same order of magnitude as the defect size) and second, the correlation residue should be small compared to $\Delta\mathbf{G}(t) \otimes f(t)$. The second condition means that the noise sources should be both uncorrelated and well distributed over the plate surface or at least, as will be explained later, spatially stationary between the acquisitions with and without defect.

More recently, Chehami et al., have proposed a statical model which quantifies the accuracy of the GF reconstruction called "RNL" to "Relative Noise Level":

$$\mathrm{RNL}(N_s) = \frac{1}{N_s}\left(\frac{5}{4} + \pi\,\frac{\eta_0}{\tau_a}\right). \tag{3}$$

As a consequence, for accurate retrieval of a Green's function, the reconstruction error must diminish when increasing the number of sources N_s, the damping time τ_a, and small plate area. One interesting result is that optimal reconstruction quality would be achieved for negligible attenuation ($\tau_a \gg \eta_0$). In that case $\mathrm{RNL} \simeq (\alpha - 1)/N_s$, which implies the existence of a lower bound of the RNL equals to $5/4\,N_s$ and $2/N_s$ for the rectangular and the chaotic plate, respectively.

The principle of the imaging algorithm used here is based on in back-propagating each element of indexes (i, j) of the matrix $\boldsymbol{\Delta}\mathbf{C}$ according to the current pixel position (x, y). The back-propagation function (bpf) of $\boldsymbol{\Delta}\mathbf{C}$ is given by [11]

$$\mathrm{bpf}_{(x,y)}(\omega) = \sum_{i=1,j=1(i\neq j)}^{N_R,N_R} \boldsymbol{\Delta}\mathbf{C}_{ij}(\omega)\, e^{j\,[d_i(x,y)+d_j(x,y)]\,k(\omega)}, \tag{4}$$

where $d_i(x, y)$ is the distance between the ith receiver and the pixel at position (x, y), $k(\omega)$ is the wave number of the Lamb mode A_0, $\boldsymbol{\Delta}\mathbf{C}_{ij}(\omega)$ is the Fourier transform of $\boldsymbol{\Delta}\mathbf{C}_{ij}(\mathrm{t})$ and N_R is the number of elements in the array (eight in this example). Then, by inverse Fourier transform, the pixel energy at position (x,y) is obtained by integrating the back-propagation function over time T_0 (accordingly to the approximation of back-propagation in an infinite plate), i.e.,

$$E(x, y) = \int_{-T_0/2}^{T_0/2} \left|bpf_{(x,y)}(t)\right|^2 \,\mathrm{d}t, \tag{5}$$

where T_0 is typically the inverse of the bandwidth.

The bpf function leads to a constructive sum and a maximum of the pixel intensity on the defect location [11]. As for pixels located elsewhere, the obtained intensity is made up of a summation of non-coherent contributions (including correlation residues $\boldsymbol{\Delta}\mathbf{n}$, reverberated wavepackets, grating lobes).

To estimate the differential correlation matrix, the 8 receivers record the ambient noise during $T = 60$ s. The operation is performed one time without the defect and one time with the defect. Then the subtraction of the correlation matrices is performed.

The noise is produced on the plate by rubbing continuously and manually the whole plate surface with a soft scrubbing pad. Material fatigue often appears in the

form of local change of physical properties. Therefore we have tested three kinds of defects:

Type of defect	diameter	thick	depth
hole	15 mm	3 mm	3 mm
massive inclusion	8 mm	3 mm	3 mm
surface crack	30 mm	1 mm	2 mm
through-crack	30 mm	1 mm	3 mm

The beamformed images obtained with a massive inclusion and hole in the plate are displayed in Fig. 1. We observe that despite the fact that the inclusion is smaller than the hole, the spurious lobe level is higher for this last. This can be explained by the fact that the scattering strength of a hole is quite small for flexural waves.

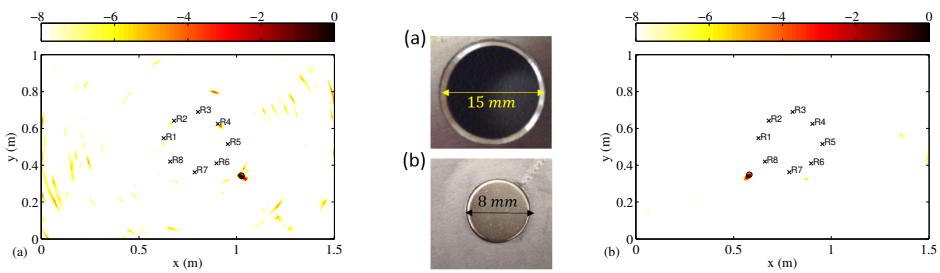

Fig. 1. Beamformed images obtained from $\Delta\mathbf{C}$ resulting from frictional noise in dB scale. (a) a hole of 15 mm of diameter, located at $(1.025, 0.343)$ m (center of the hole). (b) a massive inclusion of 8 mm diameter, located at $(0.58, 0.348)$ m (center of the inclusion).

The next challenge is to detect a surface crack and a through-crack. Results for both cracks introduced above are presented in Fig. 2. As can be seen, the defects are successfully detected in both cases because the cracks strongly interact with the acoustic field. The quality of the image obtained with the through-crack informs us about the satisfying reconstruction of the Green's functions. However what is detected here is the strongest point of the defect which is likely the edge of the groove and the shape of the defect is not recovered. To achieve this, a complex inverse problem would have to be solved, which is completely beyond the scope of this paper.

The passive localization method presented here has been shown to be efficient and robust when considering differential mode.

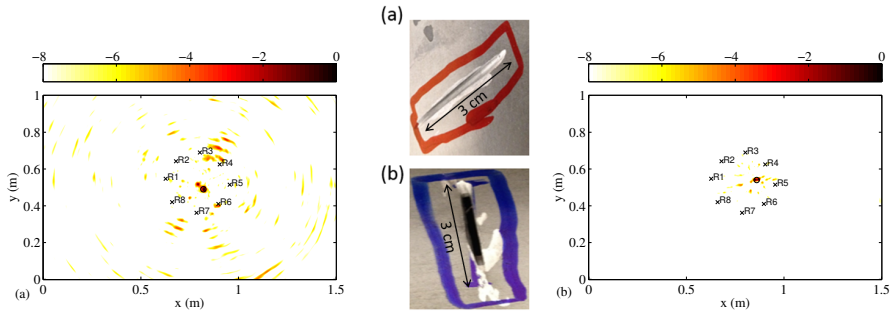

Fig. 2. Beamformed images obtained from $\Delta\mathbf{C}$ resulting from frictional noise in dB scale. (a) surface crack of 30 mm × 1 mm and 2 mm depth, located at $(0.82, 0.49)$ m (center of the crack). (b) a through-crack of 30 mm × 1 mm and 3 mm depth, located at $(0.86, 0.54)$ m (center of the crack).

3 Baseline-free repetitive probing method

In order to extend the application range of the correlation technique, a concept of a baseline-free pump-probe method is proposed here in active way for a model defect mimicking the behavior of a real nonlinear one.

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.

3.1 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. 3).

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. 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. LF shaker parameters are so as plate continuously performs vertical oscillations, in a such a way that the position of the ball and the

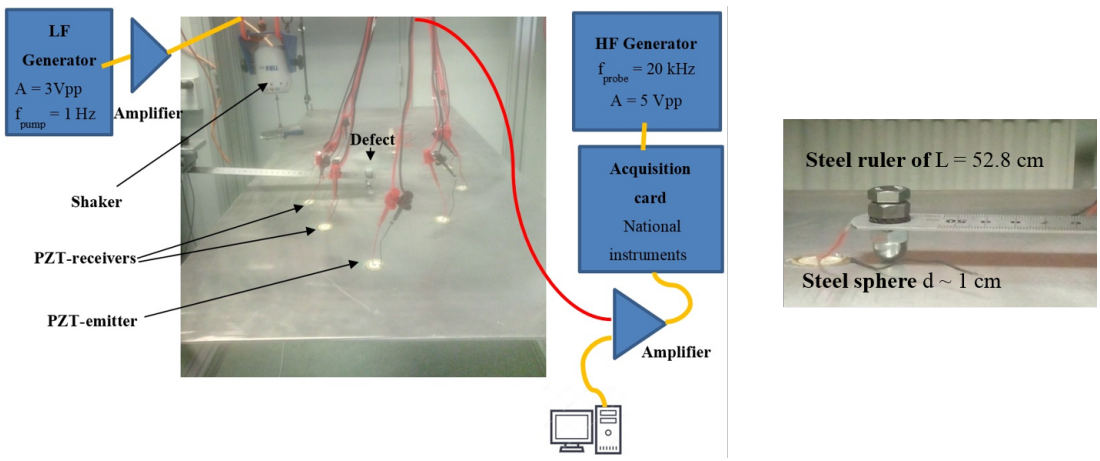

Fig. 3. (left) Pump-probe experimental setup. (right) Nonlinear defect "solid-solid" contact.

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.

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).

3.2 Signal processing and imaging results

Let us denote by s_i^j $(j = 1...M)$ the ith acquired signal at known receiver position r_j, M is the number of receiving transducers. To enhance the effect of modulation, one should make subtractions between signals at different loading states and the average of all the acquisitions, i.e.,

$$\Delta s_i^j(t) = s_i^j(t) - \frac{1}{N}\sum_{n=1}^{N} s_n^j(t), \tag{6}$$

with $n = 1...N$ acquisitions.

We obtain then N × M subtractive matrices which will be the inputs for the beamforming algorithm described in Section 2 (see Eq. 4). The pixel energy is computed according to Eq. 5. Finally, by non coherent summation we get the final image result.

The obtained results based on this repetitive probing method are shown on Fig. 4. 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 $\Delta x = \Delta y = 5$ mm. One of the transducers array is used as emitter for each figure.

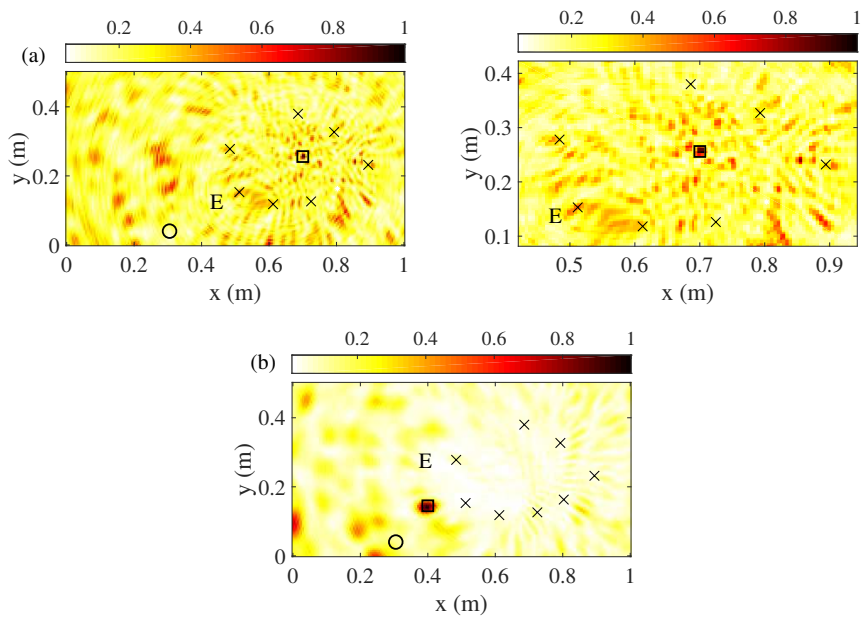

Fig. 4. Imaging localization results obtained for a nonlinear solid-solid contact located at: (a) [0.695,0.264] m, and (b) [0.4,0.145] m. (a-right) Zoom on the receivers area. The positions of the shaker and defect are, respectively, indicated by a circle and a square. E is the emitter.

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., [12]),

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. Finally, we should mention that some problems can occur if during the experiment acoustic emission (squealing effects) appears.

4 Conclusions

In this work, we have firstly presented an experimental validation of a passive technique for defect localization in metallic plates. We have successfully detected defects from noise generated by different sources between 10 kHz and 40 kHz. Using noise correlation approach, we have experimentally shown that the method is suitable and robust to detect holes, massive inclusions and even surface or through cracks in the plate. Second, 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. These preliminary experiments are very promising for Structural Health Monitoring applications and are expected to be of considerable value in the future. Further work will focused on the improvement of the SNR images and adapting the current algorithm for passive baseline-free SHM, without need of ultrasonic emitter.

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