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REFERENCE-FREE DAMAGE LOCALIZATION BASED ON PUMP-PROBE MEASUREMENTS

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ABSTRACT

Nondestructive testing is often based on comparison between experimental data measured on damaged and intact samples. However, properties of intact samples can change with time, temperature or other external factors. An alternative approach discussed here solely uses data obtained on a damaged sample under varying loading conditions. In our experiments, a series of ultrasonic probe pulses excite a Lamb wave in a thin aluminum plate subject to vibrations, while damage is modeled with a steel ball pressed against the plate. LF vibrations produce changes in contact stresses and displacements which, in turn, slightly modulate each HF reverberation record. By subtracting recorded HF signals from each other we get an array of data that finally allow us to locate the contact. To do so, we apply a backpropagation algorithm in which the differential data are multiplied by phase terms accounting for the Lamb wave propagation from the source to the receiver via a certain point on the plate (pixel). All different contributions from all the receivers are averaged producing a function having the dimension of energy. It was shown that if a pixel is located on an intact zone of the plate, particular contributions are summed up in an incoherent way which results in zero average. An essential peak is obtained only when the pixel is located at the contact. The eventual image was additionally enhanced by application of a special technique that includes random signs for each back-propagated contribution. Without changing the fact that the peak corresponds to a pixel located on damage, each set of random signs change contrast of the obtained image. The final image corresponds then to maximum contrast.

1. INTRODUCTION

In general, many structural health monitoring (SHM) and non-destructive testing (NDT) approaches are based on the comparison of test data to baseline data. The "baseline data" term intends here a set of data associated with a pristine structure subjected to all possible environmental and operational variations, such as fluctuations in temperature,

variations in surface moisture or external loading, structure aging, etc. A lack of data in the baseline or wrong match between the test data and the baseline can adversely affect measured signals and cause false alarms.

Thus, baseline SHM methodology requires a large amount of data and therefore is compute-intensive. For this reason, new NDT concepts that do not rely on previously obtained baseline data are of particular interest. A few baseline-free (or reference-free) methods have been recently proposed.

One of the attempts to reduce baseline data amounts consists in using a so-called instantaneous baseline [1]. In this approach, Lamb wave propagation along several paths is interrogated in pitch-catch configuration with a distributed transducers array. Common features in the undamaged paths are considered as instantaneous baseline and used for damage prediction.

Time reversibility of Lamb waves [2] allows to use Time Reversal (TR) method for damage detection. In [3] damage index is used to evaluate the difference between input and TR reconstructed signals for the distributed sensor array. The threshold for damage index distinguishing "undamaged" and "damaged" paths was established comparing damage indices of the paths with each other. In [4] the analysis is based on the comparison between stationary and rotating blade states. Dividing into forward and backward propagating waves, applying a standing wave filter makes damage being visualized. It was concluded [5], that TR is low-sensitive to environmental and operational variations but, on the other hand, there are significant limitations such as necessity to employ narrowband signals to minimize dispersion and a large number of transducers required for precise localization. Another similar approach relies on breaking of the Reciprocity principle in the context of delamination detection [6].

Another idea is applied in an instantaneous baseline group of methods based on mode conversion [7]. It benefits from polarization characteristics of collocating PZT transducers attached to the opposite surfaces of a thin plate. Guided waves excited across different transducer pairs al-

low damage identifying.

In this paper, we describe a baseline-free imaging method capable of contact acoustic nonlinearity (CAN) localization in thin plates. This method is based on a pump-probe experiment, in which information of damage is provided by differences in high frequency (HF) probe signals measured under varying low frequency (LF) pumping. Defect is localized by means of the back-propagation algorithm developed in [8]. This imaging method has been applied (see Chehami et al. [9, 10]) for linear defects such as holes or rigid inclusions. Numerous linear SHM techniques rely on damage indices based on parameters such as change in wave velocity and amplitude, mode conversion, wave scattering, etc. However, the impedimental factor of these linear techniques is their susceptibility to operational and environmental variabilities. Moreover, linear techniques are primarily not sensitive to nonlinear defects (such as cracks, delaminations, debondings and other CANs), which means they cannot be used for early warning.

Here, the back-propagation algorithm has been adapted for a model defect mimicking the behavior of a real CAN. In the reported experiments, a steel ball pressed against an aluminum plate is used to mimic a CAN. 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 Section 2, the experimental procedure and signal processing are described in greater detail, as well as results of imaging. Section 3 presents concluding remarks.

2. REPETITIVE PROBING EXPERIMENT: SETUP AND SIGNAL PROCESSING

2.1 Experimental setup

In the presented experiment study acoustic waves and vibrations are excited in a thin aluminum rectangular plate (1 m \times 0.5 m \times 3 mm) horizontally suspended with elastic strings on a metallic support cage. Instead of real defect we use a 1 cm steel ball pressed against the top plate surface with elastic steel ruler fixed on the same support. (see Fig. 1.).

In the plate two acoustic signals are generated (see Fig. 2): a high-frequency probe (100 ms burst with one cycle of 5 V peak-to-peak sine at 20 kHz) and a low-frequency harmonic pump in the frequency range from 0.5 to 4.5 Hz (which is much lower than f_{probe}). The probe signal is emitted by piezoelectric wafer glued to the plate surface. The pump wave is excited by a vibrating shaker firmly attached to the plate with the use of two polyurethane foam slices for preventing a direct mechanical contact that can be detected as a defect. In addition to the emitting piezoelectric wafer, there are $N_r = 7$ receiving transducers of the same kind fixed at known positions. The signals are amplified and then recorded using National Instruments acquisition board (500 kS/s, 8 channels). The

duration of the high frequency probe reverberated signal is $50 \text{ ms} \ll \frac{1}{f_{pump}}$.

Exited by LF vibrations at f_{pump} produced by the shaker, the ball experiences periodic oscillations which constantly modify propagation conditions for the HF Lamb wave. The pump parameters and precompression are selected in such a way that the ball never loses the contact and does not produce squealing.

2.2 Signal processing: Repetitive pump-probe algorithm

In this series of experiments, M sets of acoustic signals are recorded at different times corresponding to different loading states. The elapsed time between two acquisitions is about 0.45 ± 0.1 s. This particular time lapse should be less than the ball movement period. Besides, the period should not be not a multiple of the time lapse. In this situation, each recorded signal will be slightly affected by a changing ball-plate contact state which corresponds to the influence of LF pumping on a real defect.

Let us denote by s_m^j ($j = 1 \dots N_r$) the m -th signal recorded at receiver r_j . Signals registered at the same receiver at different times are subtracted from each other. Each differential signal $\Delta s_p^j = s_{m_1}^j - s_{m_2}^j$ produced by acquisitions number m_1 and m_2 ($p \equiv (m_1, m_2)$) is then backpropagated using a classical imaging algorithm (see [11]). The idea is to compensate for the phase of the wave propagating from the emitter to a receiver via the candidate defect position (called "pixel"). In case of damage located at the selected pixel, an averaging of compensated signals over all possible emitter-receiver pairs results in a narrow peak at $t = 0$. However, if at the selected pixel no defect is present, the sum is destructive resulting in a noise-like waveform. By interrogating all pixels at the plate and by the multiple application of the back-propagation algorithm, a full image can be obtained.

More specifically, a back-propagation function for the given difference Δs_p^j in frequency domain is defined by:

$$bpf_{(x,y)}^p(\omega) = \sum_{j=1}^{N_r} \Delta s_p^j(\omega) e^{ik(\omega) d_{Erj}(x,y)}, \quad (1)$$

here $d_{Erj}(\mathbf{r})$ is the distance between the emitter E and the j -th receiver via the possible defect position $\mathbf{r}(x, y)$. The wavenumber k fulfills the dispersion relation of A0 Lamb mode (flexural wave). The candidate positions are organised in the rectangular grid with a spatial step $\Delta x = \Delta y = 5$ mm.

After returning to the time domain through an inverse Fourier transform, the pixel intensity at position $\mathbf{r}(x, y)$ that is calculated in time domain as an integral of the back-propagation function squared over time window T_0 :

$$I_p(\mathbf{r}) = \int_{-T_0/2}^{T_0/2} |bpf_{(\mathbf{r})}^p(t)|^2 dt, \quad (2)$$

where T_0 is typically the inverse of the bandwidth.

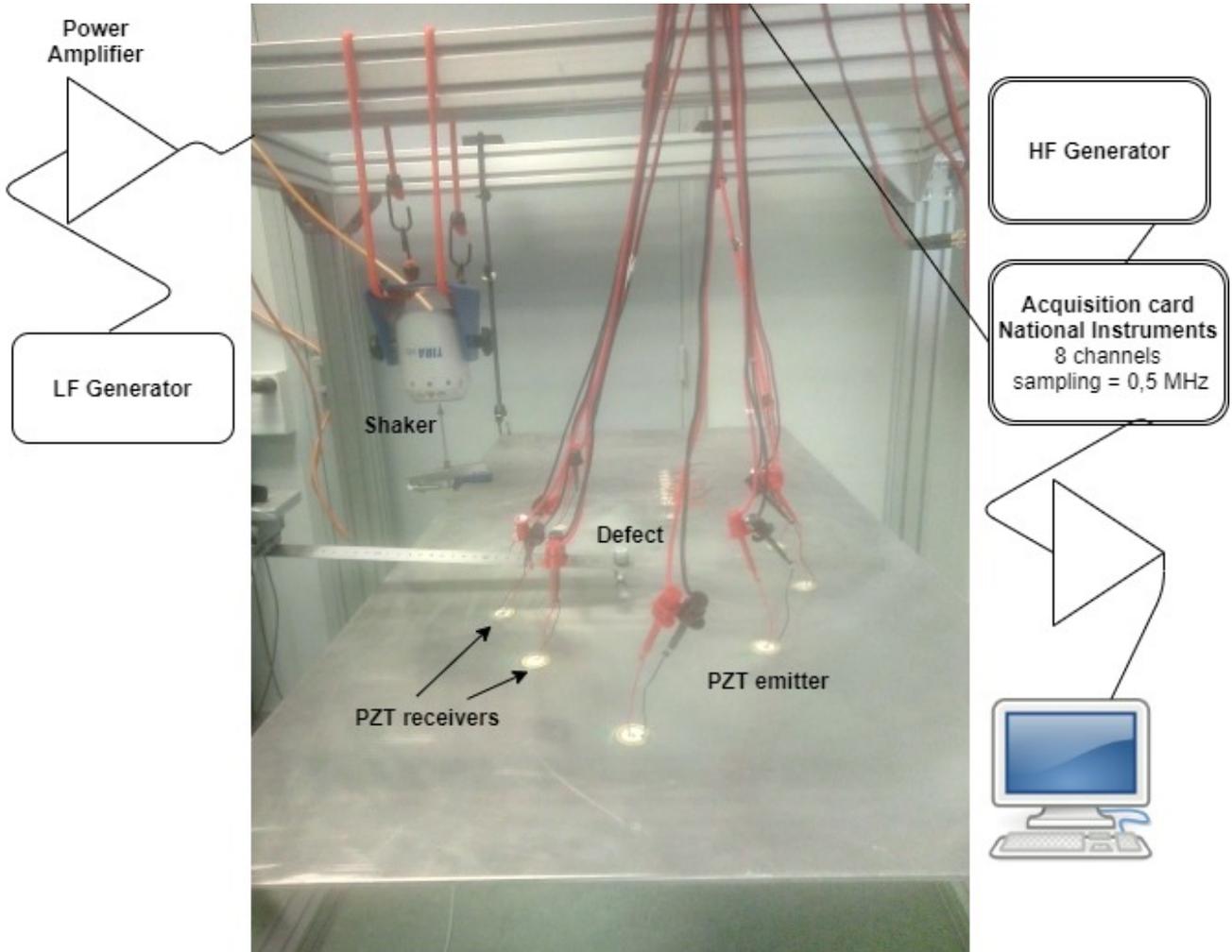


Figure 1. Experimental setup.

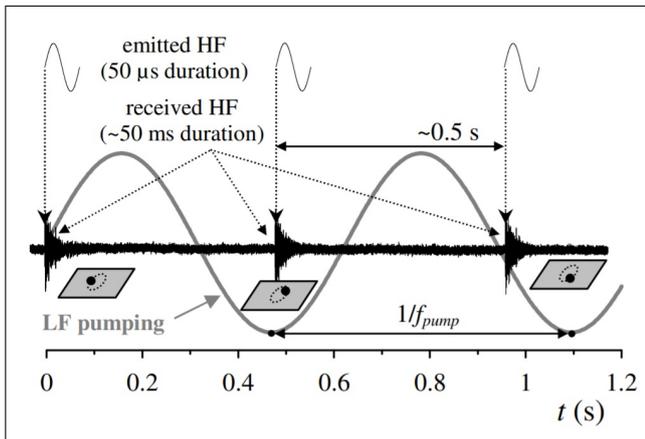


Figure 2. Typical pump-probe signals.

The intensity (2) is determined for each acquisition pair. In order to take into account all acquisition pairs and accumulate all available information, one has to sum up all individual contributions and get

$$I(\mathbf{r}) = \frac{\sum_P I_p(\mathbf{r})}{P}, \quad (3)$$

here P is number of loading states pairs. At the defect location, i.e. when $\mathbf{r} = \mathbf{r}_D$, $I(\mathbf{r})$ reaches a local maximum. Due to the incoherent summation (3) (summation of intensities) the $I(\mathbf{r})$ presents clear defect imaging (Fig. 3). At the defect location, i.e. when $\mathbf{r} = \mathbf{r}_D$, the difference between scattered fields under different loading states reveals a local maximum. Thus, an intensity of the differential signals will be much higher at the defect location, than elsewhere.

2.3 Results and discussion

The results of the measurements and signal processing are shown in Fig. 3 for different LF values. In this figure, the defect is marked with a circle, the square indicates the shaker position, the stars correspond to HF receivers.

As observed, a clear localization is obtained for the pump frequencies f_{pump} in the range between 0.5 and 4 Hz (Fig. 3). Increasing pump frequency higher or equal to 4 Hz results in no localization as shown Fig. 3d. This threshold is related to a mechanical resonance of the support system accompanied by squealing and ball detachments.

The LF response of the structure is such that for pump frequencies $f_{pump}=0.5, 2.5,$ and 4 Hz almost no horizontal

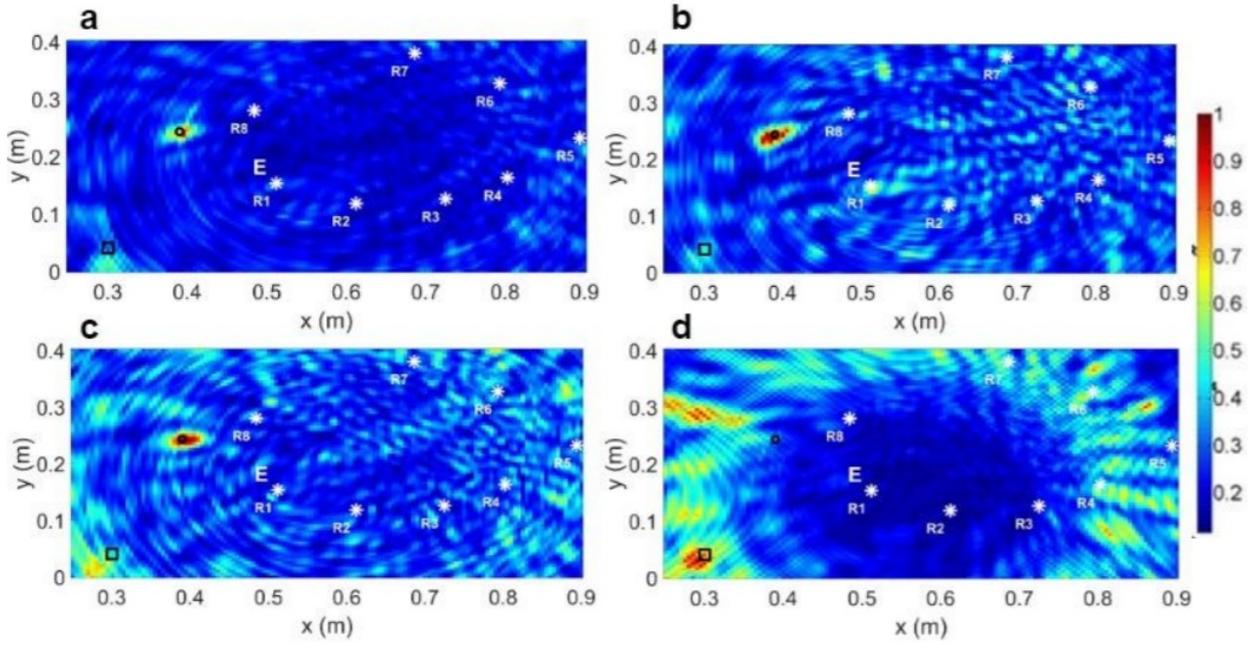


Figure 3. Imaging localization results at different pump frequencies: (a) $f_{pump} = 0.5$ Hz; (b) $f_{pump} = 1.5$ Hz; (c) $f_{pump} = 2.5$ Hz; (d) $f_{pump} = 4$ Hz.

movement of the ball relative to the plate occurs. When the movement is purely vertical, the reverberations are affected only by the Hertz-type contact nonlinearity, it simulates better the real crack with varying stress. An important fact is that the localization quality stays approximately the same regardless of the ball movement type (compare 3a,b,c and 3d).

There is a speckle-like background noise in all images, especially in Fig. 3c. It is mostly related to averaging of intensities in (2) and (3) that we had to use due to unknown signs of the defect influence on the structure for differential signals from each particular acquisition pair. Indeed, averaging of intensities using so-called "incoherent sum" does not suppress noise on the deterministic part of the signal; filtering out noise in the ranges $t < -T_0/2$ and $t > T_0/2$ solves the problem only partly.

Therefore, to improve the images signal-to-noise ratio, we propose to take into account the signs of bpf's using coherent sum as described below.

2.4 Signal processing: Random sign compensation

In many obtained images peak-to-background ratio is not optimal due to high sidelobes. In order to improve it the random sign compensation is proposed.

Purposeful non-synchronization between the pump vibrations and probe recording entails randomization of the defect state probing. The sign of the defect strength (the influence of the defect on the structure) is arbitrary and unknown in the experiment, i.e. we don't know if $bpf_{(r)}^p(t)$ experiences a positive or a negative peak.

Meanwhile, the sum in (3) is incoherent, which means that the phase information of backpropagation function (i.e. of scattered field) is discarded. Thus, squaring of

backpropagation function in (2) causes the sign loss, which in turn adds to sum in (3) a destructive component. If signs of the defect strength ε_p under different loading states were known (p refers to the pair of loading states), it would be possible to calculate the coherent sum of backpropagation functions with correct signs:

$$BPF(\mathbf{r}, t) = \sum_{p=1}^P \varepsilon_p bpf_p(\mathbf{r}, t), \quad (4)$$

and then calculate the integral:

$$I(\mathbf{r}) = \int_{-T_0/2}^{T_0/2} |BPF(\mathbf{r}, t)|^2 dt \quad (5)$$

instead of (2).

However, as the signs of the "defect strength" (further: "sign sequence") are unknown, the suggestion here is to choose them randomly and obtain an image as it is described above. After that one should test quite a large number of different sign sequences. Then comparative study is based on the concept of the "image contrast" which is retrieved from:

$$C(\varepsilon_p) = \frac{\max_{\mathbf{r}} I(\mathbf{r})|_{\varepsilon_p}}{\frac{1}{N_{pixels}} \sum_{\mathbf{r}} I(\mathbf{r})|_{\varepsilon_p}}, \quad (6)$$

here N_{pixels} stands for the number of considered candidate defect positions.

The image with highest contrast is considered as a final result (the corresponding sign sequence is an optimal one).

In the Fig. 4 the results without and with random sign compensation are shown for 1000 different sign sequences.

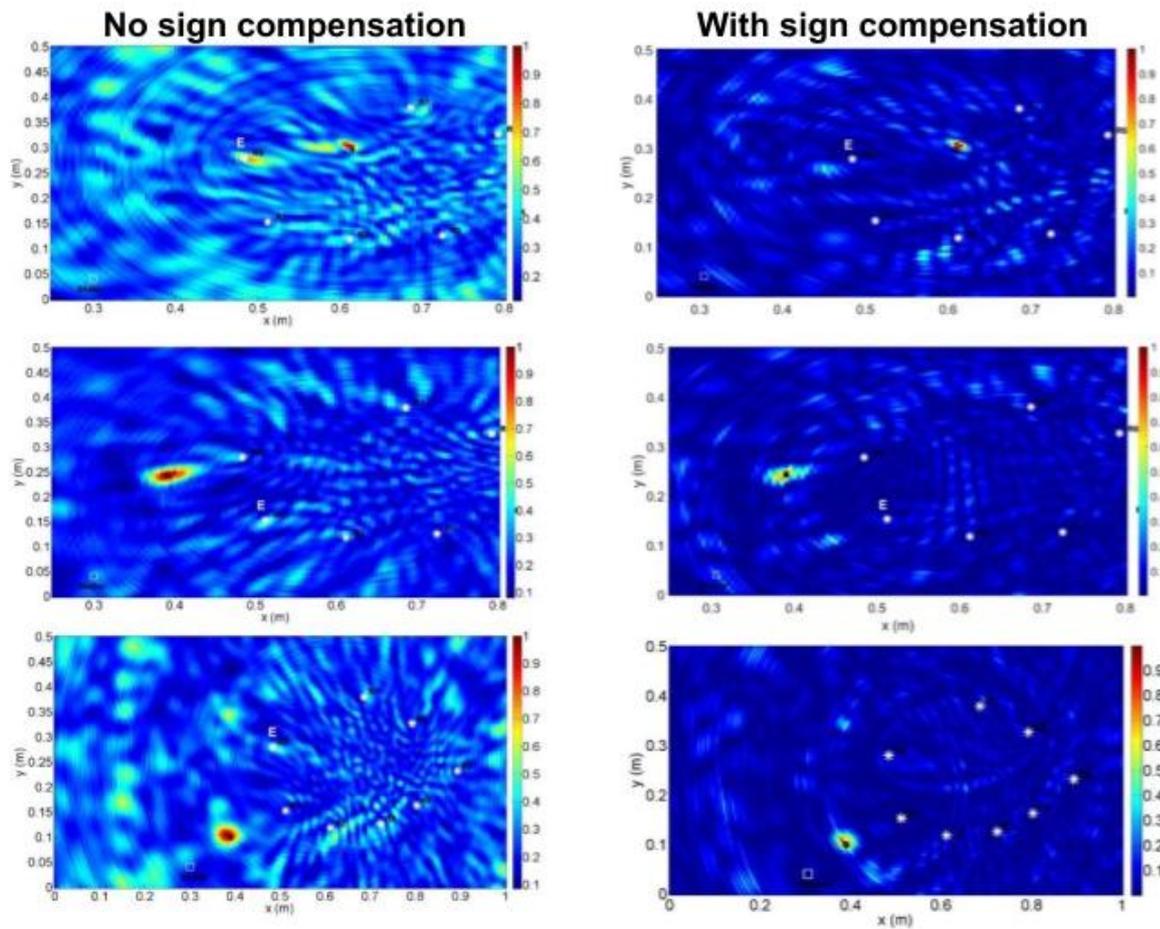


Figure 4. Imaging localization results at different defect locations at $f_{pump}=1.5$ Hz without random sign compensation (left column) and with it (right column).

It is worth noting that the application of the sign compensation technique increases the signal-to-noise ratio in 15 times; speckle-like artifacts are significantly reduced.

3. CONCLUSION

A reference-free defect localization technique based on a pump-probe SHM experiment is proposed. Preliminary measurements were conducted in a thin aluminum plate having an artificial defect (Hertz contact: steel ball pressed against the plate). The repetitive probing experiment is robust to locate the position of the contact nonlinearity related to the defect. The algorithm works for different defect positions, even for defects located outside of the zone covered by receivers or closely to the plate borders. For the certain pump amplitude below the frequency threshold of about 4Hz the defect can be successfully localized without a hypothetical reference. Signal to noise ratio of image can be increased in approximately 15 times by using the random sign compensation technique.

Future works will be focused on adaptation of the developed algorithm for passive SHM i.e. when weak ambient vibrations of a structure accompanying its operation are used instead of an active low frequency pump.

4. ACKNOWLEDGEMENT

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