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METAMATERIAL-AIDED CORRELATION-BASED SIGNAL PROCESSING FOR DAMAGE LOCALISATION

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Abstract. A sensor inspired by spiders was developed, featuring embedded metamaterial in the form of phononic crystals The metamaterial aims to filter out frequencies around the main harmonic of excited guided waves so that the piezoelectric sensors located on the spider's body listen to higher harmonics induced by damage. The correlation of the measured response and a set of measured reference data acquired at various grid points along the specimen surface allows the determination of the source of nonlinearity (damage localisation). The experiments were conducted on an aluminium alloy plate. For simplification of the experiment, the nonlinearity was simulated by the piezoelectric excitation. Reference data were collected simultaneously by piezoelectric sensors located at the spider and plate as a response to excitation on a square grid of points. Additional testing signals were collected in response to excitations at various points on the plate. Correlation coefficients were calculated between reference data and test signals as damage indicators. Damage localisation efficacy using the proposed spider-inspired sensor was compared with the case when the band-pass filter is used for signals registered at piezoelectric sensors directly attached to the plate. It has been shown that a better signal-to-noise ratio can be achieved by the use of the proposed spider-inspired sensor.

1 INTRODUCTION

The guided wave-based method is recognized as one of the most promising structural health monitoring (SHM) methods, which is reflected in a plethora of publications [1]. The damage effects on guided waves such as reflections, mode conversion, velocity change, and amplitude change are considered in the damage detection, localisation and size estimation. These techniques assume the linear wave response that is used for the development of damage indexes.

The shortcoming of linear techniques is that the operational and environmental effects (especially temperature) strongly influence the registered signals and perturb the usability of damage indexes. Moreover, anomalies caused by small discontinuities are more difficult or even impossible to extract from linear guided waves in comparison to nonlinear guided waves [2]. Therefore, recent advancements in guided wave-based SHM are related to nonlinear guided waves [3-8]. The processing of nonlinear guided wave signals is expected to improve upon early damage detection. However, the main difficulty arises due to the very small amplitude of nonlinear effects, which are often buried in the noise. It is also challenging to distinguish between nonlinear effects introduced by the equipment and structural discontinuities. Therefore, it is essential to develop suitable and effective filtering tools. In this work, we propose to aid the filtering process by using metamaterial in the form of phononic crystals (PCs).

2 GENERAL CONCEPT

Defects cause anomalies of propagating guided waves, such as wave reflections and mode conversions (linear effects) and also a generation of higher harmonics (non-linear effects). These anomalies can be potentially used for damage identifications.

The general concept of damage detection by utilizing higher harmonics is depicted in **Figure 1**. The wave packet of carrier frequency f_1 is excited at point A. The propagating wave encounters a defect which becomes the source of higher harmonics generated, e.g. due to clapping or fatigue crack breathing. The guided wave propagates further to point B where frequency components are around primary frequency f_1, and higher harmonics are represented by f_2 and f_3. Next, the propagating wave reaches the ultrasonic device that has embedded PCs responsible for filtering out the main frequency harmonic f_1. In consequence, only higher harmonics induced by defect are registered at point C. By setting a threshold, it is possible to distinguish between the healthy state and the damaged state of the structure.

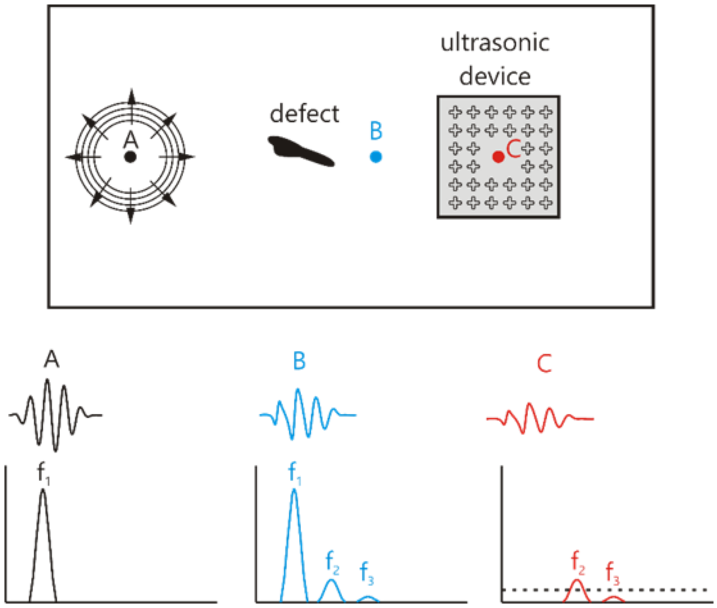

Figure 1: Metamaterial-aided defect detection by utilization of higher harmonics

2.1 Numerical tests of the time reversal method

The capabilities of the metamaterial-based device can be expanded from damage detection, as presented in **Figure 1**, to damage localisation using the time reversal method [9-11]. The principles of the time reversal method, aided by the metamaterial, are shown in **Figure 2**. The ultrasonic device is inspired by spiders, which are one of the most vibration-sensitive living creatures. They possess extremely efficient strain detectors (lyriform organs) capable of transducing mechanical loads into nervous signals embedded in their exoskeleton [12]. Spiders can process these signals and sense a prey trapped on the spider's web. The sensing capabilities of spiders have driven the design of bio-inspired solutions in terms of sensor technology reviewed in [13].

In particular, we focus our attention on the design of a spider-inspired ultrasonic device capable of guided wave filtering and sensing which is realized by piezoelectric transducers placed on the cephalothorax body [14]. In the first stage, piezoelectric transducers act as sensors. Due to the filtering properties of PCs embedded into the spider's leg, the frequency components of guided waves around the excited carrier frequency are blocked, and sensors register only higher frequency harmonics emanating from damage. In the second stage, each signal is time-reversed. Then, the time-reversed signals are applied to respective piezoelectric transducers, which work this time as actuators. Due to reciprocity conditions, a spatial focus at the damage location occurs at a certain moment in time, resembling the source of nonlinear waves. In order to localise damage or perform damage imaging, the focusing effect must be captured.

The time reversal method aided by the metamaterial was investigated numerically. An exemplary focusing effect indicating the location of the damage is presented in **Figure 3**. It can be noticed that high amplitude values are present at the damage location, actuator location and on the spider. The damage localisation is very precise but a dense spatial response of guided waves has to be acquired.

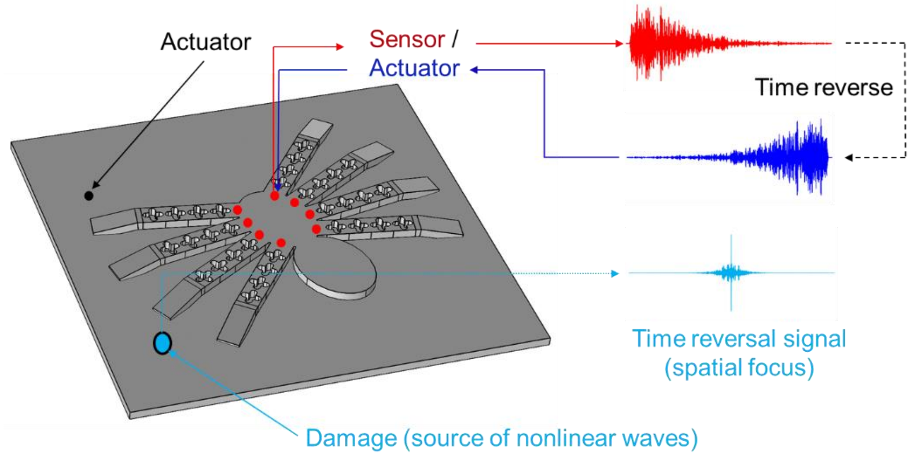

Figure 2: Principles of the time reversal method

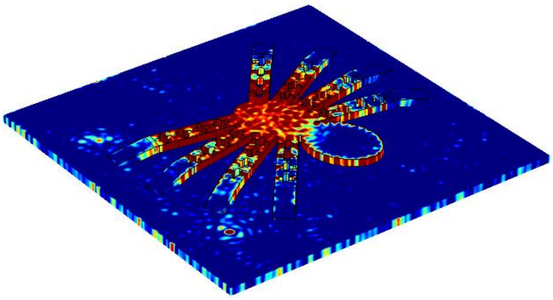

Figure 3: Damage imaging results obtained by the time reversal method (numerical data)

2.2 Correlation-based signal processing for damage localisation

Our previous work [15] showed that the correlation of the measured impact response and a set of measured reference data acquired at various grid points along the specimen surface allows high resolution in the determination of the impact point. A similar concept was tried experimentally but with the spider-inspired sensor as an element of the system (see **Figure 4**). The main difference was that instead of impact localisation, the aim was the localisation of damage-induced nonlinearity.

The spider-inspired ultrasonic device was manufactured by laser cutting a 3 mm thick aluminium alloy plate. The width of the spider at its widest point is 126 mm. The device was attached to the aluminium alloy plate by using cyanoacrylate glue. For simplification of the experiment, the nonlinearity was simulated by the piezoelectric excitation. However, an additional difference between the current experiment and the previous one was the use of a narrowband signal in opposition to a broadband signal. It was necessary to use a narrowband signal to fit the band gap of PCs embedded into the spider's legs [14]. Moreover, in the experiment, the piezoelectric transducers were used both for the excitation and the sensing in comparison to the scanning laser Doppler vibrometer used previously for sensing.

Conventional time reversal tests were performed by using two piezoelectric transducers. A narrowband excitation signal (420 kHz, 5 cycles) was used. An exemplary signal registered by a sensor is shown in **Figure 5a**. Next, this signal was time reversed, and a focusing effect was observed on the second sensor (see **Figure 5b**). The influence of the signal duration on the amplitude of the focused wave was investigated, concluding that 1 ms signal duration gives good performance and enables a considerably shorter time of experimental measurements (see **Figure 5c**).

The correlation approach was investigated next. The piezoelectric actuator attached using coupling gel was placed at a coarse grid of 5×6 points and a dense grid of 10×4 points and used for excitation of Hann windowed sine signal. Then, propagating waves were registered at sensors s1 and s2, located on the spider body as well as on sensors s3 and s4, situated on the plate, as shown in **Figure 4**. This data was considered as a reference. Furthermore, a few more actuation points were added for testing purposes, not necessarily at the cross-section of grid lines shown in **Figure 4**.

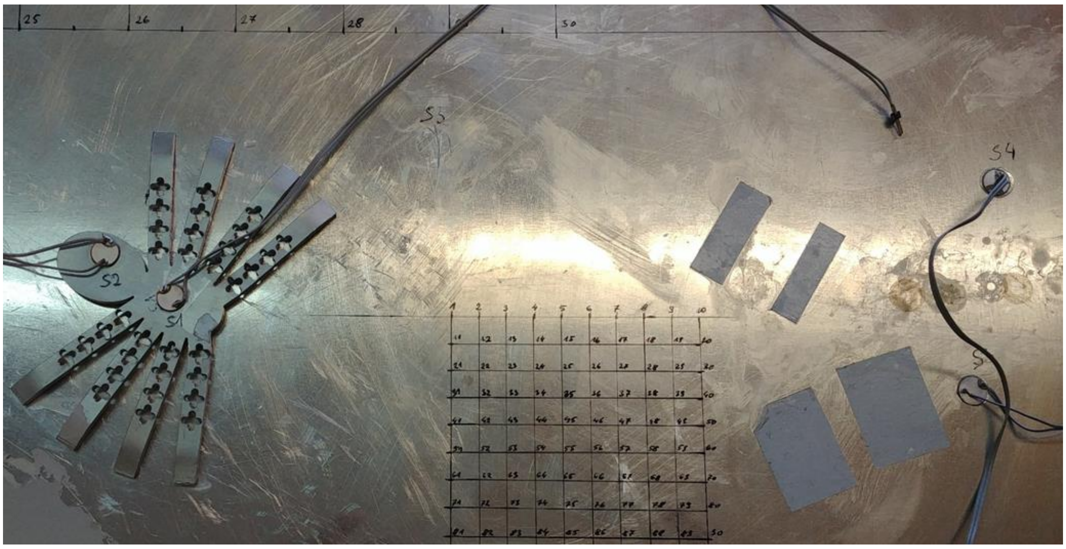

Figure 4: Spider-inspired sensor with piezoelectric transducers and grid used for non-linearity identification. Sensors s1 and s2 are bonded to the spider, whereas sensors s3 and s4 are bonded directly to the aluminium plate

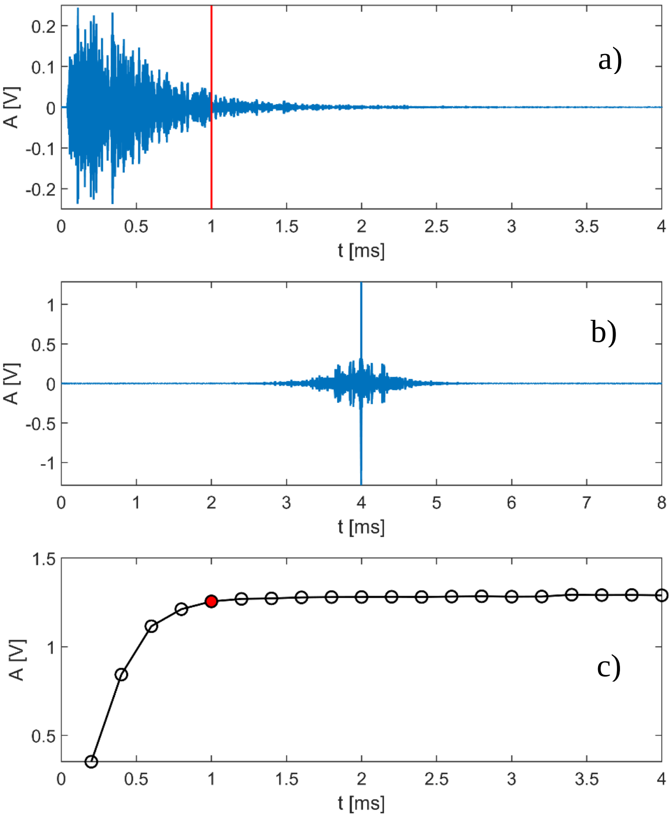

Figure 5: The effectiveness of the time reversal focusing; a) registered signal, b) reconstructed signal, c) amplitude of the reconstructed signal depending on the duration of the registered signal

Correlation coefficients were calculated between each pair of signals in reference data, e.g. for actuation at grid points 1 and 2, 1 and 3, and so on (all combinations without repetition).

The resulting values are binned and presented in the form of histograms in **Figure 6**. Correlation close to zero means that signals can be distinguished and, in turn, damage can be localised unambiguously. For a higher cycle count (10 cycles - narrow frequency band), correlation distribution is wider, leading to worse results than in the case of a lower cycle count (5 cycles). The finer grid also causes deterioration of results.

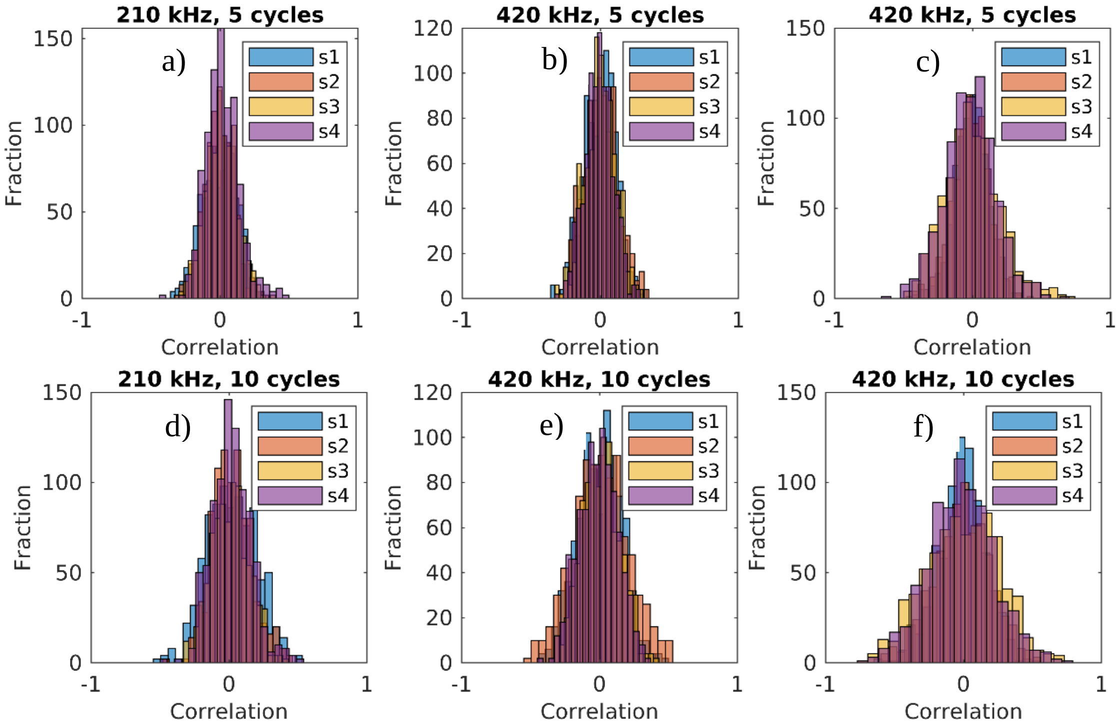

Figure 6: Correlation histograms: a) coarse grid, 210 kHz, 5 cycles, b) coarse grid, 420 kHz, 5 cycles, c) fine grid, 420 kHz, 5 cycles, d) coarse grid 210 kHz, 10 cycles, e) coarse grid, 420 kHz, 10 cycles, f) fine grid, 420 kHz, 10 cycles

Several correlation-based damage localisation tests were performed, and only selected ones are shown in **Figure 7** and **Figure 8** for the case where test points were close to the intersection of grid lines. Bars represent correlation coefficients calculated between the reference signal at the grid point and the test signal. The higher the correlation coefficient, the higher the probability of damage at this particular grid point. It can be noticed that considerable SNR improvement is obtained by using more piezoelectric sensors and combining the results calculating a product of sets (see **Figure 7**). This means that it can be worth installing more piezoelectric transducers on the spider (e.g. one transducer per leg as was shown in the numerical example).

Furthermore, in most cases, an analogue filter in the form of PCs embedded into the spider-inspired sensor leads to better SNR than digital filtering. For example, for damage located close to grid point no 3, when direct signals registered at sensors s1 and s2 situated in the spider's body are used to calculate correlation coefficients, the SNR is 9.2 dB. In comparison, when the band-pass filter is used for signals registered at sensors s3 and s4 located on the plate, the calculation of correlation coefficients leads to the SNR value of 5.3 dB.

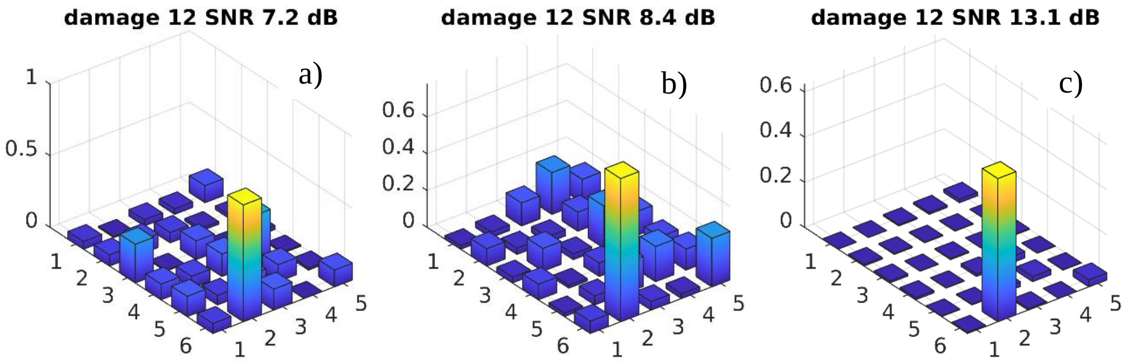

Figure 7: Correlation-based damage localisation results by the use of signals from: a) sensor s1, b) sensor s2, c) combined results for sensor s1 and sensor s2 (damage located close to grid point no 12)

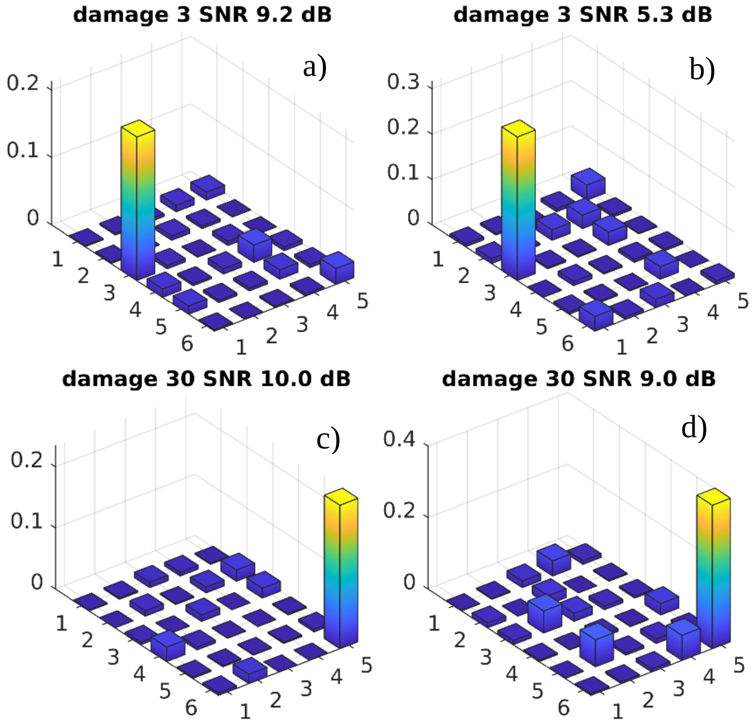

Figure 8: Correlation-based damage localisation results by the use of a), c) spider-inspired sensor, b), d) digital filtering

3 CONCLUSIONS

The spider-inspired ultrasonic device with PCs embedded into legs was manufactured and tested. The time reversal method in combination with the spider-inspired sensor was tested numerically, showing great potential for damage localisation.

It was confirmed experimentally that the correlation of the measured response and a set of measured reference data acquired at various grid points along the specimen surface allows the determination of the source of nonlinearity (potential damage). The parametric studies revealed that excitation signals with a wider frequency band (fewer cycles) would be preferred, but the limiting factor is the width of the band gap in the designed phononic crystals. Additionally, the more sensors on the spider's body the better signal-to-noise ratio and, in turn, damage localisation. Moreover, it was shown that the analogue filtering by using PCs embedded into the spider's leg could be better than the application of a pass-band digital filter.

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