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IDENTIFICATION OF LOCAL DEFECT RESONANCES USING GLOBAL AND LOCAL MODE SEPARATION PROCEDURE

MATEUSZ KRZEMIŃSKI*, ANDRZEJ KLEPKA* AND ŁUKASZ PIECZONKA*

* Dept. of Robotics and Mechatronics
AGH Univ. of Science and Technology
30 A. Mickiewicz Ave., 30-059 Cracow, Poland
e-mail: klepka@agh.edu.pl

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Abstract. The article presents an approach to developing a novel algorithm for effective Local Defect Resonance (LDR) detection to improve the quality and automate structural integrity assessment. The proposed technique is applied to samples with different sizes of damage. The research is conducted in parallel with virtual and experimental models. To excite the structure, the specimen was instrumented with a surface-bonded low-profile piezoceramic transducer. Scanning laser vibrometry was used to obtain response signals from the plate. The frequency characteristics were determined for individual points in the structure based on the response signal and the known excitation. The algorithm uses the amplitude difference between the local damage area and the entire structure as a background. On this basis, local defect resonance parameters are determined.

1 INTRODUCTION

The increasing use of advanced materials requires accurate and complex health monitoring techniques for assessing structural integrity. Among them, a novel non-invasive method that uses sonic or ultrasonic frequency excitation tuned to the defect to activate its resonant response was proposed by Solodov et al. (2011) [1]. The principle behind this is that embedded defects result in a local loss of stiffness that gives rise to characteristic resonant frequencies of the defect itself, known as Local Defect Resonances (LDR). As for the classical modal testing approach, the match between excitation and LDR frequency corresponds to the maximum wave-defect interaction. The energy delivered by the impinging wave is selectively trapped within the damaged area, leading to a significant increase in the defect response amplitude. This increase is strongly localized in the defect area, providing an excellent contrast between damaged and intact specimens. Solodov et al. (2013) [2] further applied the concepts of LDR to a Flat Bottom Hole (FBH). Experimental results were validated through FEM modeling. An analytical formulation was proposed to determine LDR frequencies of defects like FBH, delaminations in composite materials, and laminar defects in rolled sheet metals. In the following work, Solodov et al. (2019) [3] developed an analytical solution for different planar defect shapes, validated through a series of experimental tests. The experiments combined a wide-band chirp signal with a laser vibrometer of the specimen surface.

The laser Doppler vibrometry was also used by Hettler et al. (2016) [4] to extract LDR damage frequencies in aluminum plates and glass-fiber reinforced polymer (GFRP). Moreover, it has been demonstrated that LDR behavior does not limit itself to out-of-plane direction but can be extended toward in-plane characteristics (Segers et al. 2018 [5], 2019 [6]). Experiments on different types of defects, i.e. FBH, surface cracks, and BVID, showed a clear in-plane LDR at a high-frequency range due to the high in-plane bending stiffness. Even though many papers deal with the LDR frequency for imaging the damage itself, few attempts were made to develop a robust algorithm to identify the LDR frequencies among the system's natural frequencies, making the procedure cumbersome and time-consuming. Starting from the analytical formulation proposed by Solodov et al. (2019) [3] it can be applied only for a few classes of idealized defects and only when the geometry and position of the defect are known, as well as the material properties. Hettler et al. (2016) [4] proposed an imaging-based algorithm in which Otsu's algorithm identifies possible LDRs. More recently, Roy et al. (2019a [7], 2019b [8]) proposed an approach based on the bicoherence analysis to obtain the LDR of FBH in aluminum plates and delamination in the GFRP composite plate. The current study suggests a novel algorithm for the efficient detection of LDR to improve quality and automate assessing structural integrity. The proposed technique is based on modal analysis examination. This paper presents the work done to develop, validate, and verify the method's effectiveness. Firstly, we describe the algorithm in Section 2. The test sample and experiment setup are described in Section 3. Damage detection and localization results are presented in Section 4. Finally, the paper is concluded in Section 5.

2 LOCAL DEFECT RESONANCE: AUTOMATED EXTRACTION

Local Defect Resonances due to local loss of stiffness are specific to the selected area of a structure. Hence, vibrations in the corresponding frequencies are localized in such areas with negligently small background response of the rest of a structure. It indicates that for the local modes, the amplitudes in the areas of damage are significantly higher than the mean value of the amplitudes of the whole structure. In this same method, we work with amplitudes of frequency response functions of structures by calculating their medians and applying several mathematical operations. We operate on maps, which are the matrices of dimensions equal to the dimensions of a measurement grid – the number of points in rows and columns. The algorithm starts with calculating the median factor for each measurement point. It his generates the matrix A_{med}

$$A_{med} = \begin{bmatrix} median(A_{w1}) \\ \vdots \\ median(A_{wm}) \end{bmatrix} * [median(A_{k1}) \dots median(A_{kn})] \tag{1}$$

where A_{wm} is the *m* row and A_{kn} is the *n* column of the measurement points grid. Matrix A_{med} is normalized by a factor *s* producing matrix A_s, also called here a structural map

$$A_s = s * A_{med} \tag{2}$$

where $s = \frac{mediana(A)}{mediana(A_{med})}$ and A is a matrix of amplitudes in a single frequency, also called an amplitudes map. By subtracting the structural map from the amplitudes map, we receive an irregularities map A_I

$$A_I = A - A_s \tag{3}$$

Having frequency response functions (FRF) for all the points of a structure, we can then calculate *MCR* values for all measurement points and frequencies

$$MCR = \frac{A_I}{mean(A_S)} \tag{4}$$

Then, selecting the maximum MCR value for each frequency gives MCRmax characteristic. It contains information about the relative differences between points with the highest amplitudes and mean values for a whole structure. The higher the value is, the more distinct LDR is detected. The minimum peak prominence and height determine the threshold for LDR frequency selection. The first coefficient is a sum of the mean and standard deviation of prominence, and the second is the standard deviation of MCRmax values for the whole characteristic. It allows automatic LDR frequency detection. The concept and main steps of the calculations are shown in Figure 1.

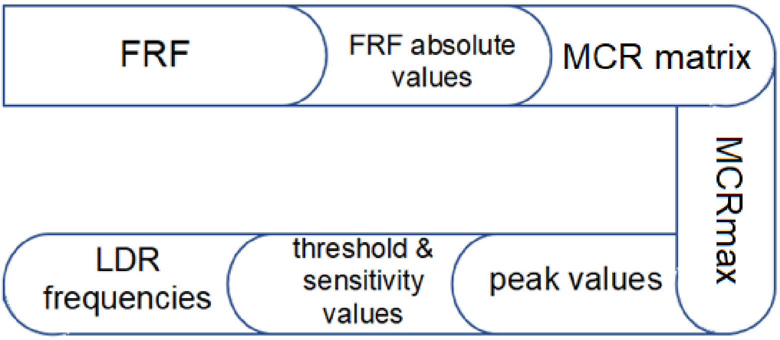

Figure 1: Automatic LDR extraction algorithm flowchart

3 EXPERIMENT: TEST SAMPLE AND METHOD

A modal analysis test was performed to obtain the required input for the algorithm. For the presented work, the test sample made of poly(methyl methacrylate) (PMMA) was manufactured for the experimental testing of the algorithm's operation. The dimensions of the plate are as follows: 300 × 300 × 18 mm. Damages of FBH-type were introduced in the plate to represent three sizes of deep defects with nominal diameters of 58, 40, and 18 mm.

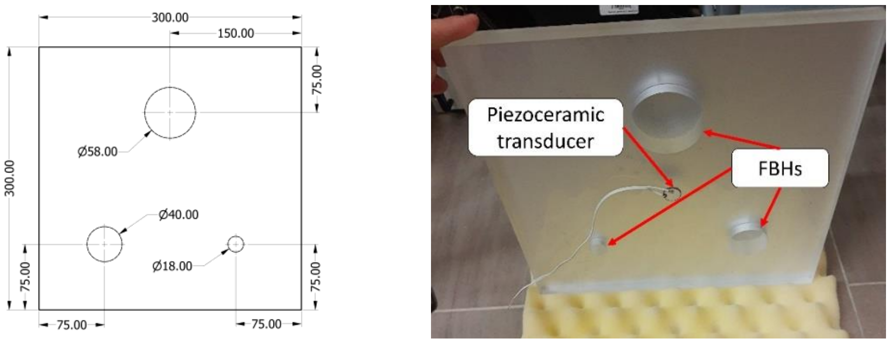

Figure 2: PMMA test sample with FBHs: nominal dimensions in [mm] and the sample prepared for experiments

The designed depth of all FBHs was 17 mm, corresponding to the 1 mm thickness of the residual material in the damaged area. The test specimen and its dimensions are presented in Figure 2. Please note that the sample drawing is presented from the intact side view, while the manufactured sample is presented from the damaged side perspective.

Our initial research employing the finite element analysis has proved that in the 20kHz bandwidth, LDRs should be present for the examined test specimen. The sample was freely suspended to avoid nonlinearities from boundaries and modally excited using a piezoelectric transducer located at the center of the plate. A chirp signal was used to excite the sample with a frequency range of 0.5 to 20 kHz and a peak-to-peak amplitude of 8 V. An external signal generator generated the excitation signal, amplified ten times with the power amplifier and passed on the piezoceramic transducer. Experimental modal analysis was performed using laser vibrometry. A Polytec RoboVib PSV500 1D laser was used for non-contact measurements of out-of-plane vibration responses. A measurement grid was composed of 362 equally distributed points and covered the whole sample surface. Each measurement point was averaged three times with a single measurement time of 2.048 s. The Frequency Response Functions (FRF) were calculated from the experimental input and output data using the Polytec software. The experimental arrangement for the modal analysis test is presented graphically in Figure 3.

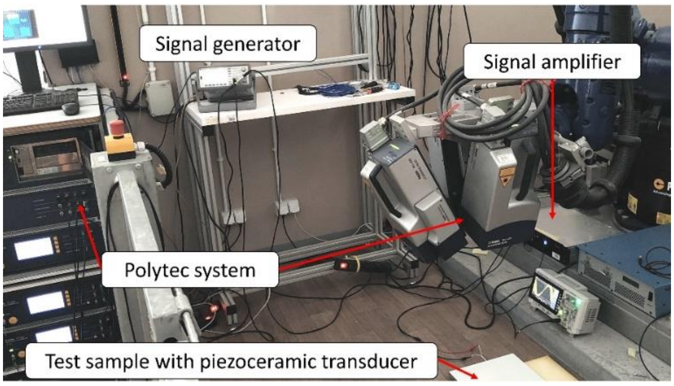

Figure 3: Experimental modal analysis setup **-** configuration with piezoceramic transducer

4 RESULTS

Obtained from the experiment FRFs were used to calculate MCRmax characteristic (Figure 4).

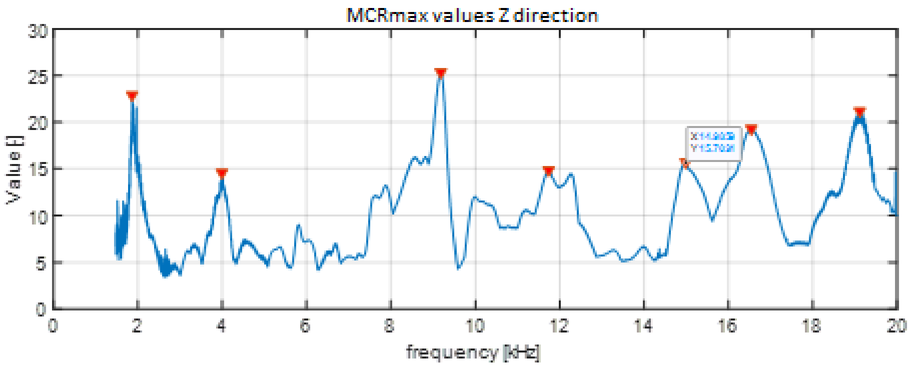

Figure 4: MCRmax characteristic of the tested PMMA sample

In a defined frequency range, many eigenfrequencies correspond to global and local resonances can be found. The peak density and MCRmax values were analyzed. Considering the broad total frequency range of the measurement, we received very good references as a background in contrast to local phenomena. This is especially visible for identified LDRs. Next, the automated LDR frequency selection was applied to the MCRmax characteristic. The peaks are visible. The peak values are significantly above the mean value of the characteristic. Identified LDR frequencies apply to different flat bottom holes.

Using Polytec software, we visualized mode shapes. All frequencies the algorithm selects are Local Defect Resonance frequencies and identify structural discontinuity, its presence and location. The visualizations of LDRs of the FBH Ø58 mm allow for determining its location and shape (Figure 5). The excitation of the second out-of-plane mode of LDR of FBH Ø58 mm was accompanied by the first out-of-plane mode of LDR of FBH Ø40 mm. It must also be noted that the algorithm also found higher LDRs, but the presentation is limited to the first two ones (first and second out-of-plane modes).

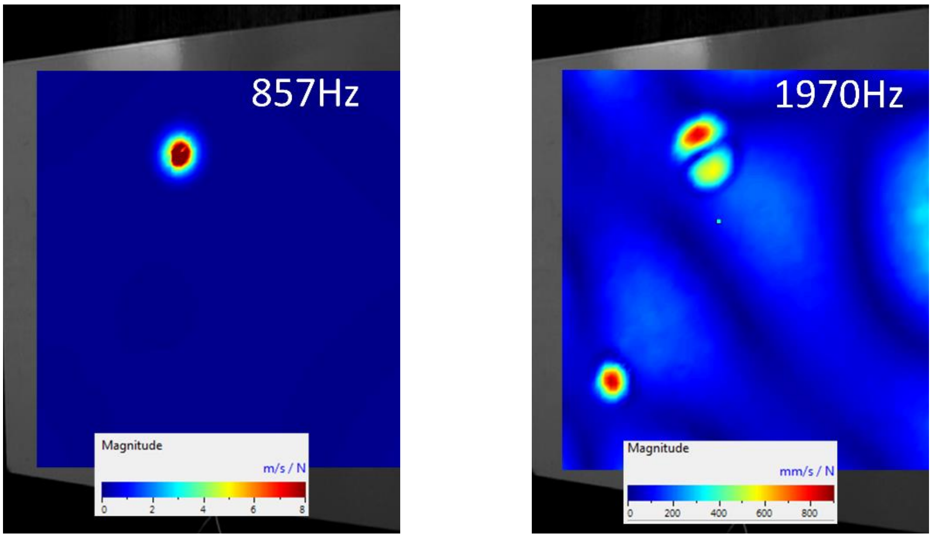

Figure 5: PMMA test sample modeshapes – FBH Ø58 mm

In the FBH Ø40 mm case, the algorithm correctly identified the first two modes of out-of-plane LDRs (Figure 6).

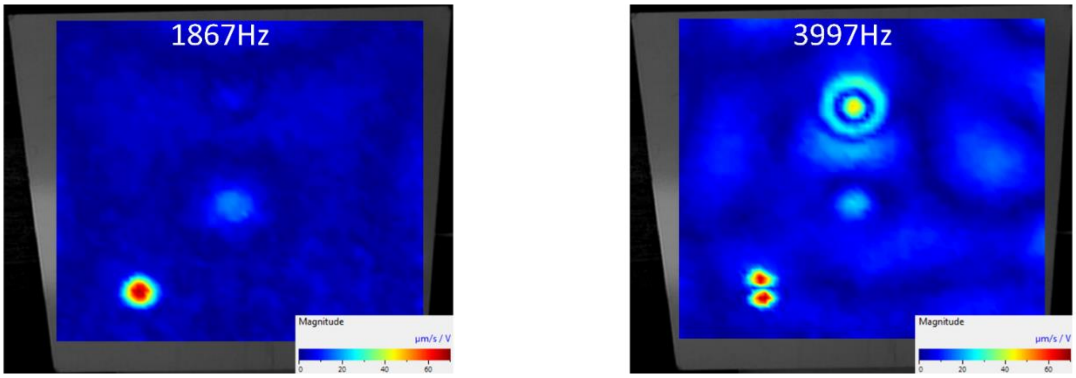

Figure 6: PMMA test sample modeshapes – FBH Ø40 mm

The FBH Ø18mm is the other defect for which the algorithm's indications are true positive. The visualizations of first and second out-of-plane LDRs of FBH Ø18 mm extracted by the algorithm for various datasets are depicted in Figure 7.

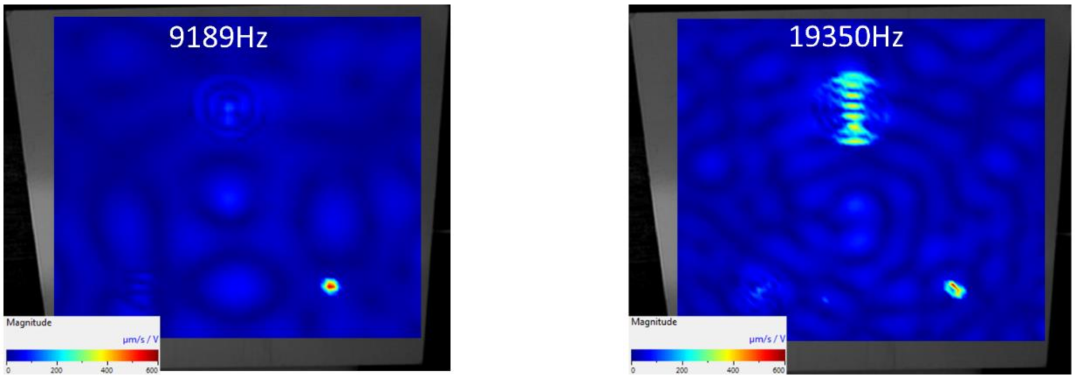

Figure 7: PMMA test sample modeshapes – FBH Ø18 mm

5 CONCLUSIONS

A novel algorithm was developed for Local Defect Resonances selection, structure discontinuity detection, and localization. A PMMA test sample with flat bottom holes was used to validate and verify the method. An experimental modal test was performed to complete the analysis. The results demonstrate the propriety of the algorithm operation. The determination of LDRs is satisfactorily efficient. Identified frequencies correspond solely to local vibrations of damaged areas.

Further research work is required to confirm the robustness of the algorithm. More different samples and materials should be investigated. Future work should also include damaged composite structures concerning out-of-plane and in-plane phenomena.

Acknowledgment

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