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EXPERIMENTAL DETECTION OF PLATE CRACKS USING OPERATIONAL MODES OBTAINED WITH FULL FIELD LASER DOPPLER VIBROMETER MEASUREMENTS

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Abstract. *Aging structures and safety issues create a growing demand for structural health monitoring (SHM). Crack propagation, rusting and other kinds of damage can compromise the structure behavior and cause catastrophic events. Cracks are related to material or geometric discontinuities and static and dynamic stress concentration. In this work, image processing techniques are applied to the displacement field obtained with a numerical model, build to simulate a plate with a notch, and to the velocity fields obtained experimentally over a notched plate surface, excited with a sinusoidal force. The results are used to indicate the existence and location of the notches. Wavelet decomposition combined with the Sobel edge detector approach, high pass spatial filtering, and a high pass spatial filtering effect obtained using the Regressive Discrete Fourier Series (RDFS) are used and compared.*

Keywords: *SHM, Image Processing, Wavelets, Edge Detector, RDFS*

1. INTRODUCTION

Vibration-based analysis has evolved in the past decade as a promising method for SHM. The premise of vibration-based SHM is that dynamic characteristics of a structure are a function of its mechanical properties. Thus changes in these mechanical properties as a result of localized structural damage will result in observable changes in the dynamic characteristics vibrations of the structure (Reda Taha *et al.*, 2006). Cracks are related to material or geometric discontinuities and static and dynamic stress concentration (Ostachowicz, 2008; Palacz & Krawczuk, 2002). To simulate them, a numerical finite element model was built and a plate was damaged with notches. Its stationary dynamic behavior was measured with a Laser Dopler Vibrometer (LDV).

Some Operational Deflection Shapes (ODS) at selected frequencies on the measured and simulated plate surface are used to show the influence of the notches on the vibration patterns, depending on the preponderant mode, at a given frequency. ODS are bidimensional data and can be considered as an image, for each frequency, that should be chosen so that a sufficiently high wavenumber is excited leading to wavelengths small enough to detect the crack. The magnitude and location of the notches are not clear when observing the displacements over the plate (for a given frequency displacements and velocities are proportional). Therefore, it is necessary to enhance the images (displacement or velocity field at a given frequency) in order to localize the faults. In this work, some techniques, such as a High Pass (HP) wavenumber spatial filtering, High Pass spatial filtering using RDFS approach, Sobel Edge Detector and Wavelet Decomposition are used to detect and localize the faults. This techniques are hoped to be useful together with diagnosis algorithm, to automatically detect damage in regions of interest, using spatially distributed measurements.

First, only the HP wavenumber filtering is applied to the simulated displacement field and measured velocity field. Then, RDFS smoothing is applied to the non-filtered velocity field and subtract from the original one, leading to a HP spatial effect. Later, Sobel Edge Detector is applied to the non-filtered displacement and velocity field with and without the RDFS treatment. Finally, Haar wavelets are used to perform decomposition with and without the RDFS treatment. The first level of decomposition is shown for the simulated data and also the second level of the Haar decomposition is shown for the measured velocity field.

2. IMAGE PROCESSING TECHNIQUES APPROACH

2.1 High-Pass Filtering

It is well known that the disturbance caused by abrupt displacement changes has a bigger impact at higher frequencies, where wavelengths are smaller. Therefore, a first approach is to use a HP wavenumber spatial filter, with a cutoff frequency in the two-dimensional wavenumber domain (k_x, k_y) given as follows:

$$k^2 \leq k_x^2 + k_y^2 \quad (1)$$

$$k = \left(\frac{\rho h \omega^2}{D}\right)^{1/4} \quad (2)$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (3)$$

where ω is the selected frequency, in rad/s, being analyzed, k_x and k_y are the wavenumbers along the x and y axis, respectively, E is the Young's Modulus, ρ is the mass density, ν is the Poisson coefficient and h is the plate thickness.

2.2 Regressive Discrete Fourier Series (RDFS)

Another spatial filtering and smoothing approach is the RDFS (Arruda, 1992). The main application of this technique is to smooth surfaces as a Low Pass (LP) filter, but with less sensitivity to spatial leakage effects at the borders. The HP effect is reached by subtracting the smoothed response from the original one. The two-dimensional RDFS uses four parameters: p and q, the number of wavenumber components in each direction, and α and β, the ratio of the RDFS period and the DFT equivalent period in each direction, since the RDFS period is arbitrary.

2.3 Sobel Edge Detector

Edge Detectors are well known in image processing and there is a wide diversity of proposed techniques. Suitable introduction to Edge Detectors can be easily found at the literature, for example in Gonzales (2002). Patsias & Staszewski (2002) applied wavelet approach to edge detection at optical measures to detect damage. In this work, Sobel edge detector is applied to the displacement and velocity field for simulated and measured data, respectively. It calculates its spatial derivative and uses a preset threshold to find the discontinuity, what can be useful to detect damage. This method needs pre-processing to enhance the crack response, otherwise any place where the derivative threshold was reached will be considered a notch, which can be generate numerous spurious points on the plate borders. RDFS will be used here to perform that.

2.4 Wavelet Transform

The Wavelet decomposition approach can be used as a tool for SHM and, although with no clear physical meaning. The wavelet's scales can be useful to detect damage (Reda Taha *et al.*, 2006; Sohn *et al.*, 2004; Wang & Deng, 1999). First applications of wavelets to damage detection are reported by Surace & Ruotolo (1994), Wang & McFadden (1996a) and Wang & McFadden (1996b), using the transient behavior of time signals in a one point measurement. Here Wavelet Transform is not used as a time-frequency analysis tool (Quian, 2002; Strang & Nguyen, 1996), but as a decomposition tool to detect discontinuities in images (Gonzales, 2002).

A WT of a signal leads to a time-scale representation. For each ODS, the wavelet coefficients obtained for the spatially distributed velocity field are analyzed. Scales can be seen as a match between the spatially distributed velocity field and the mother wavelet, but with a localized behavior instead of the whole field as in a Fourier series(Reda Taha *et al.*, 2006). Hence, a natural choice for a mother wavelet is the Haar wavelet, due to its abrupt changing aspect. Using numerical and analytical beam models, Wang & Deng (1999) has shown that the Haar wavelet is able to detect cracks from spatially distributed structural response measurements for reduced number of points, while the Gabor wavelet needs a higher spatial resolutions. Treat spatially distributed data using the wavelets coefficients request an agreement between the number of scales used and the image definition, because of the decimation in the decomposition process (Quian, 2002; Strang & Nguyen, 1996).

3. NUMERICAL AND EXPERIMENTAL DATA

3.1 Numerical Model

A numerical model using the Finite Element approach was used to simulate a cracked plate. A $1m \times 1m \times 1mm$ plate was meshed with 20×20 Kirchhof plate elements (Cook, 1995), with no constraint at the boundaries, and one transversal $0.5m$ notch was simulated using elements with null mass and elasticity proprieties at the middle of the plate. The displacement field was considered to perform the proposed analysis, using harmonic excitation.

3.2 Experimental Setup

To simulate material or geometric discontinuities an aluminum plate was damaged with notches, as shown in Fig. 1, and its stationary dynamic behavior was measured with a scanning LDV. The plate was suspended with fishing lines to perform the measurements. It has dimension $600 \times 800 \times 0.9$ mm and was measured with $49 \times 70 = 3430$ grid points, spaced of 10 mm. To estimate the FRF at each grid point, the plate was excited by a electrodynamic shaker applying a sinusoidal sweep starting with 20 Hz up to 700 Hz. The mean was estimated using ten measurements. LDV measurements consider the velocity fields, but for a given frequency displacements and velocities are proportional.

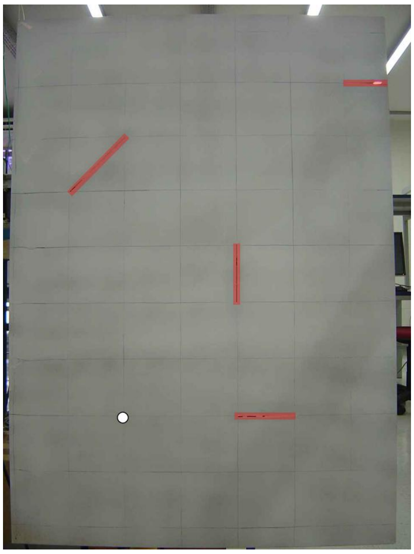
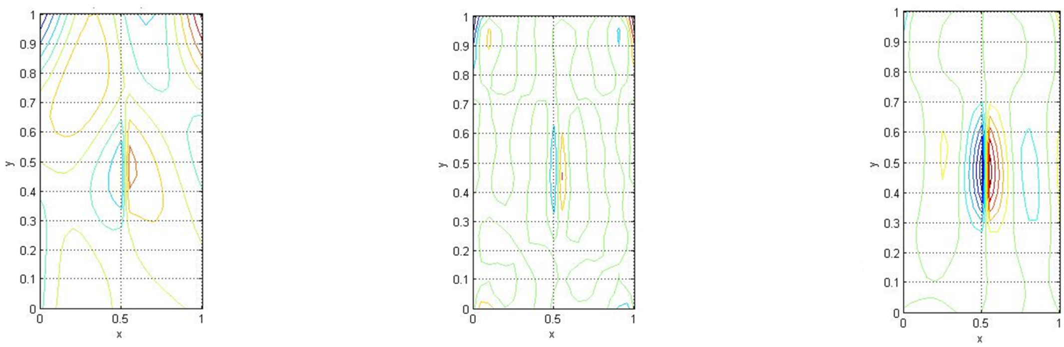


Figure 1. Plate with notches suspended with fishing lines excited by an electrodynamic shaker with a periodic chirp signal (exciter location indicated by a round white mark and notches location indicated by a red mark).

4. RESULTS

The numerical model was excited using a 20 Hz sinusoidal signal. Fig. 2(a) shows the displacement field of the plate. Note that the influence of the notch is clear, but has the same magnitude of the border effect. Fig. 2(b) show the results for HP filtering, showing that despite of keeping the border effect this influence is smaller than the non-filtered displacement field. Fig. 2(c) shows the displacement field using the RDFS approach obtained for $p = q = 10$ and $\alpha = \beta = 1.5$. Note that the influence of the border effect at the displacement field is minor compared to the crack effect.

The Sobel edge detector was applied to the displacement field without any pre-processing, shown at Fig. 3(a), and with the RDFS approach, shown at Fig. 3(b). Note that the RDFS approach was able to enhance the crack effect, avoiding the border effect. Haar WT was applied to displacement field and lead to good results without any pre-processing to enhance the crack effect, as shown at Fig. 4.



(a) (b) (c)

Figure 2. (a) Non-filtered response (b) HP filtering approach and (c) RDFS approach for selected ODS of the displacement field.

Figure 1 shows a picture of the measured plate. The exciter location is indicated by a round white mark and notch locations are indicated by red marks. For some selected ODS one can see, in Fig. 5, the influence of the notches on the vibration patterns, depending on the preponderant mode at a given frequency, but the magnitude of this influence is not clear when observing the magnitude of the displacements over the plate (for a given frequency displacements and

(a) (b)

Figure 3. Sobel edge detector not enhance (a) and enhanced and with RDFS approach (b) for the numerical model.

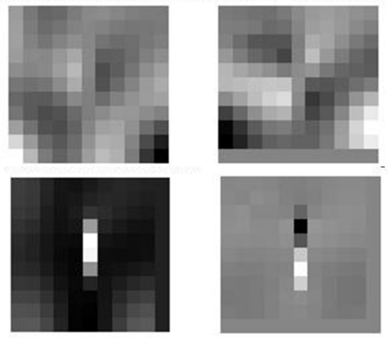


Figure 4. Haar WT of the displacement field. First level of decomposition. Approximation Coefficients (upper left), Horizontal Detail Coefficients (upper right), Vertical Detail Coefficients (lower left), Diagonal Coefficients (lower right).

velocities are proportional).

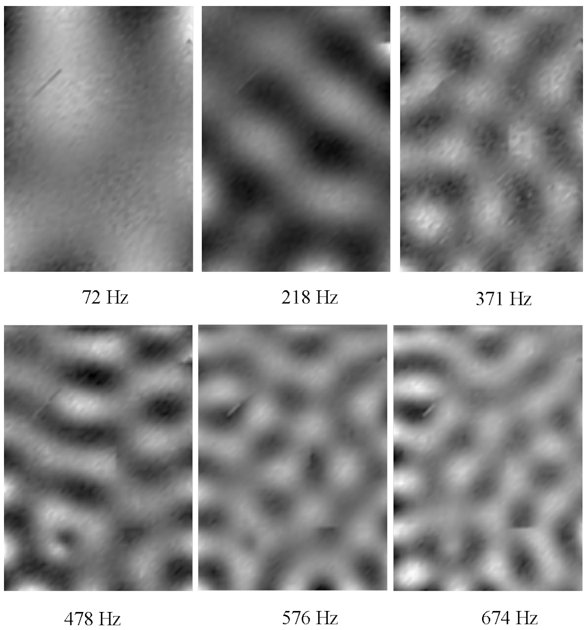


Figure 5. Selected ODS for the velocity field.

From Fig. 5 it is possible to note that the crack effect has the same magnitude of the velocity field. Therefore, it is necessary to enhance the images in order to localize the faults. HP filtering is performed to enhance the image, using the cutoff frequency in the two-dimensional wavenumber domain, chosen as in Eq. 1, Eq. 2 and Eq. 3 and it is showed in Fig. 6(a). This approach does not show good results because the border's effect at high wavenumbers is similar to the notch effect. The magnitudes are much higher, thus hiding the notches.

In order to reduce the spatial leakage effects at the border, the RDFS smoothing is applied. Figure 6(b) shows the results obtained for $p = q = 10$ and $\alpha = \beta = 1.5$. It can be observed that for different ODS frequencies there are different sensitivities to the notches. In fact, the RDFS smoothing was successful in enhancing the notches from the velocity field in spite of the border effects.

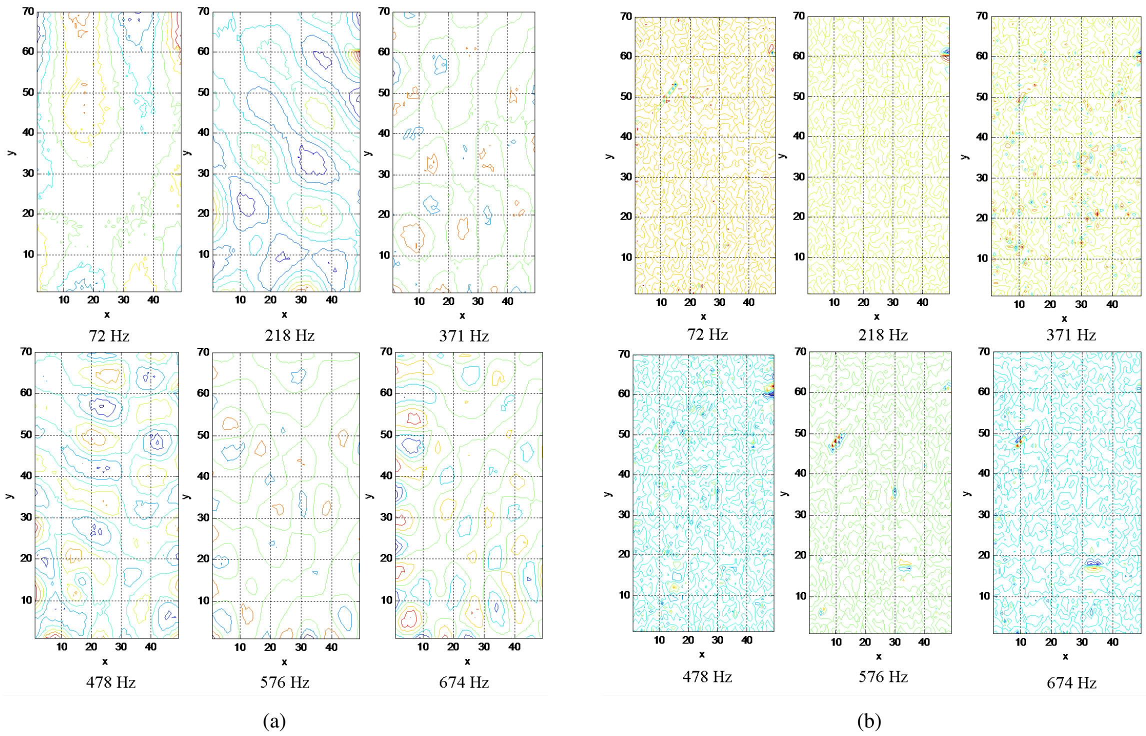


Figure 6. (a) HP wave number filtering approach and (b) RDFS approach both for selected ODS of the velocity field.

The Sobel edge detector was performed using the Image Processing Toolbox of Matlab© . Figure 7 compares the Sobel edge detector results for selected frequencies with and without RDFS spatial filtering, with 50% peak value threshold. It is worth noticing that the RDFS spatial filtering improves the edge detection by reducing the leakage effects, mainly at the plate borders. It is also important to note that the image coordinate system was changed due to Matlab features.

The Wavelet decomposition approach was also performed with and without RDFS smoothing. Fig. 8 and Fig. 9 show the approximation coefficients and horizontal, vertical and diagonal coefficients for Haar wavelet first and second level of decomposition for the displacement field at the selected frequencies without RDFS spatial filtering, respectively. Fig. 10 and 11 show the approximation coefficients and horizontal, vertical and diagonal coefficients for Haar wavelet first and second level of decomposition for the displacement field at the selected frequencies without RDFS spatial filtering, respectively.

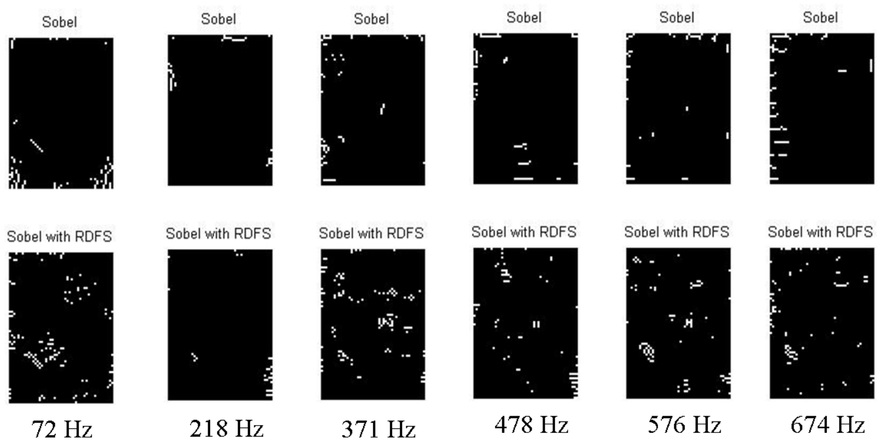


Figure 7. Sobel edge detector enhanced and not enhance with RDFS approach for selected ODS of the velocity field.

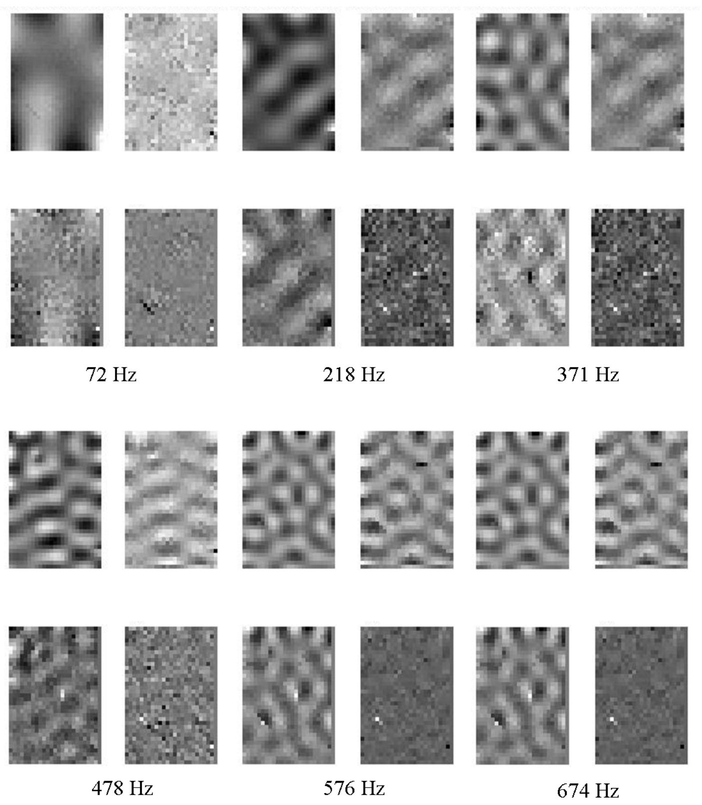


Figure 8. Haar WT without RDFS approach for selected ODS of the velocity field. First level of decomposition. For each ODS: approximation Coefficients (upper left), Horizontal Detail Coefficients (upper right), Vertical Detail Coefficients (lower left), Diagonal Coefficients (lower right).

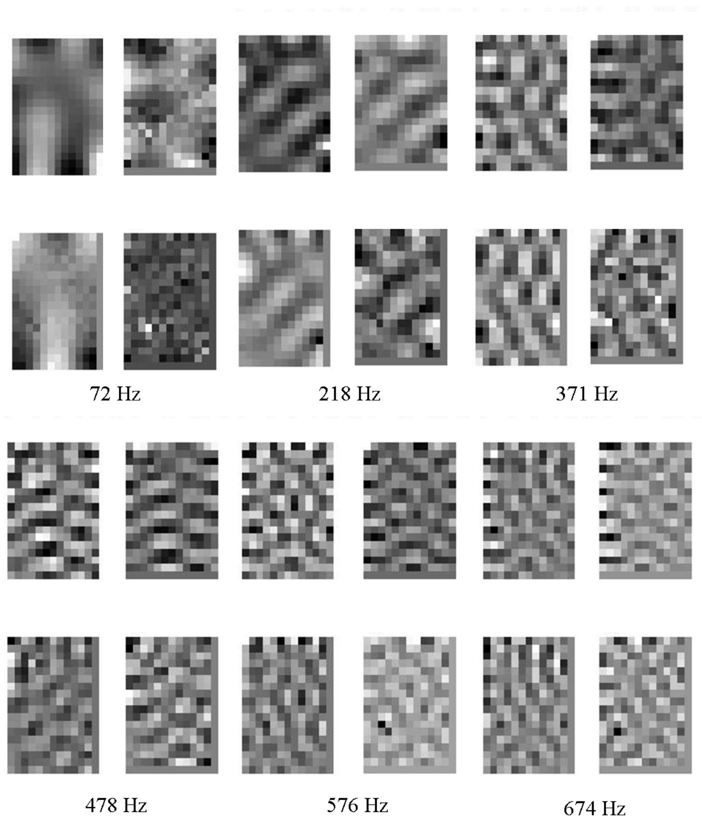


Figure 9. Haar WT without RDFS approach for selected ODS of the velocity field. Second Level of decomposition. For each ODS: approximation Coefficients (upper left), Horizontal Detail Coefficients (upper right), Vertical Detail Coefficients (lower left), Diagonal Coefficients (lower right).

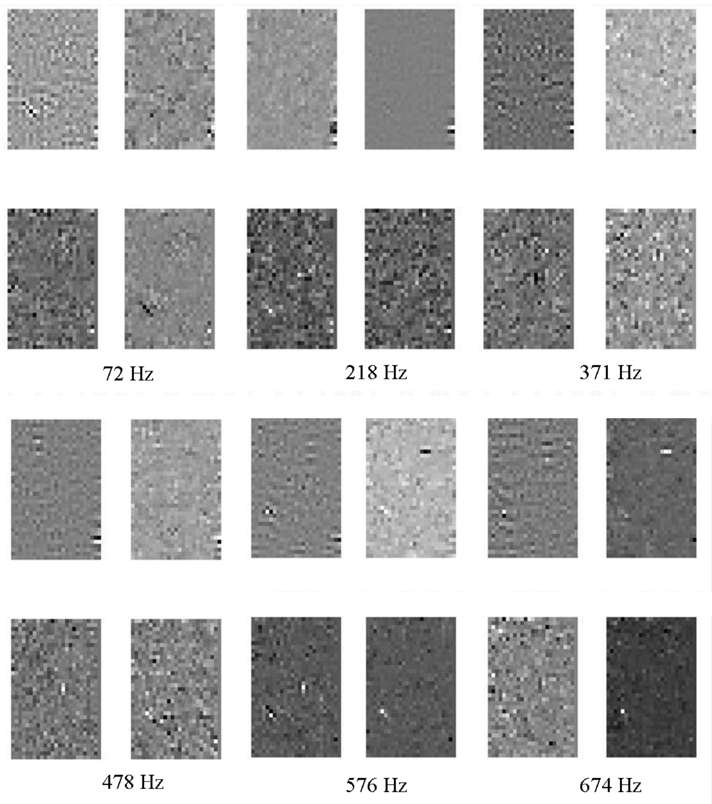


Figure 10. Haar WT with RDFS approach for selected ODS of the velocity field. First level of decomposition. For each ODS: approximation Coefficients (upper left), Horizontal Detail Coefficients (upper right), Vertical Detail Coefficients (lower left), Diagonal Coefficients (lower right).

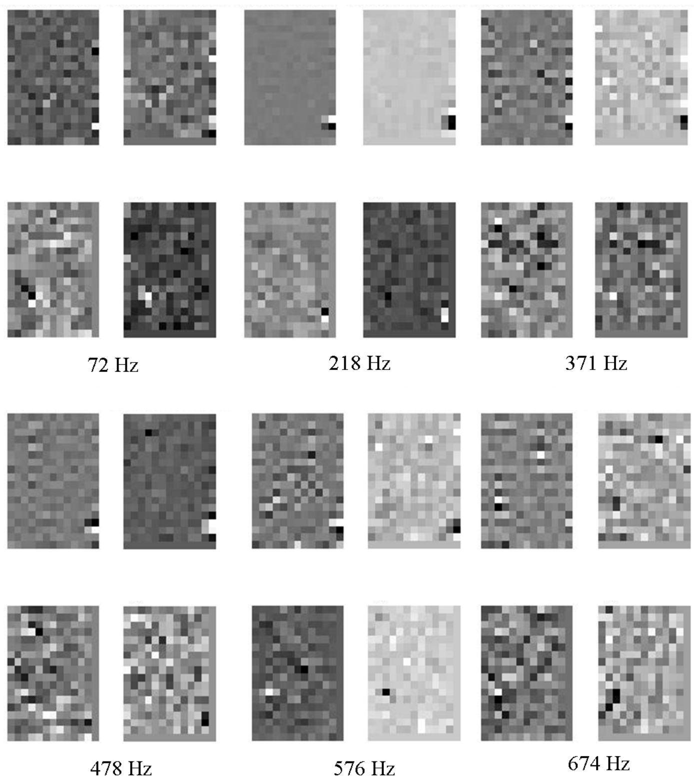


Figure 11. Haar WT with RDFS approach for selected ODS of the velocity field. Second Level of decomposition. For each ODS: approximation Coefficients (upper left), Horizontal Detail Coefficients (upper right), Vertical Detail Coefficients (lower left), Diagonal Coefficients (lower right).

5. CONCLUSIONS

Results shown here indicate that the image processing of the displacement or velocity fields obtained over a plate surface excited with a sinusoidal force (ODS) can indicate the location of notches made on the plate. The preponderant mode was shown to have a great influence on the crack identification. Therefore, some ODS were chosen to apply the image processing techniques.

The best results were obtained using the RDFS to enhance the crack effects despite border effects and ODS magnitude. Yet, the HP wavenumber spatial filtering can be considered improved as a enhancement tool. There is a wide diversity of proposed edge detectors that can be investigated in order to localize cracks. Sobel edge detector is just one of them. The WT has been widely used to localize cracks as a time-frequency tool and it was presented here as image processing technique applied to displacement and velocity field. This approach is considerably improved when used together with RDFS as a HP spatial filtering.

Systematic detection techniques may be designed to indicate locations where faults can exist, thus facilitation the inspection task. This work is a first effort is order to reach that. The excitation in a real life application could be done without contact by an acoustic source. The frequency should be chosen so that a sufficiently high wavenumber is excited (small enough wavelength), and any full field vibration measurement technique such as SLDV, ESPI, or acoustic holography can be used.

6. ACKNOWLEDGEMENTS

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8. Responsibility notice