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Application of the LPD (Laser Photo Deflection) Method to the Vibrational Diagnosis of a Brick Wall

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Abstract

In this paper, we present the results of the optical evaluation of the vibrational behavior of a wall (brick). The procedure used is Laser Photo Deflection (LPD), where a laser beam reflected off the sample is redirected to a deflection detector, which detects the sample’s vibrations. Using various excitation alternatives, it is possible to establish definitely the first 10 Eigen vibration modes, from which a simple formation pattern based on 2 digits (n,m) can be clearly recognized, for example mode (1,1) (the fundamental mode) corresponds to 29.4 Hz and mode (2,1) to 37.3 Hz, and so on.

Keywords: Physics; Engineering (Structural vibrations; Resonance; Eigen frequencies; Sound excitation; Optical measurements; Laser photo deflection)

Introduction

The diagnosis of a structure based on its vibrational response is a technique in civil engineering that is not yet fully developed and is less widely practiced. Based on the experience accumulated in our group, using the nonconventional technique (LPD) in the evaluation of various structures [1, 2], we can assert that the evaluation and inspection of the resonant vibrations of the structure is one of the best criteria for establishing its condition. In an initial study by our group in 2006, we were tasked with measuring the vibrational response of a wall optically. The obtained resonance spectrum was an irregular succession of small peaks [3], unlike the ordered succession also observed on that occasion in the evaluation of a roof. In this regard, we were only informed that the wall had suffered a slight fracture and that it was repaired.

In this work we also evaluate a wall using the LPD method and, as will be shown in what follows, the resonance pattern obtained is extremely defined and precise. Even more, we are now convinced that even a microscopic crack in the structure can be detected by analyzing its resonances, despite being invisible to the naked eye.

From us, this work constitutes a further contribution to our task of systematically studying different basic construction elements, with the primary objective of understanding the accumulation of vibrations that occur in a building [4], limiting ourselves in this case, as indicated, to study the vibrations of a brick wall, whose results can be justified through a simple Mathematical relationship.

Materials and Methods

The procedure, applied in this work, to study the vibrational resonances of a structure is a non-traditional optoacoustic method developed by our group in recent years [1, 2], and which we call: LPD (Laser Photo Deflection). This technique is based essentially on generating small vibrations (micro-vibration) with sound and detecting these by measuring the deflection of a laser beam that originally hits the structure and is reflected from a mirror attached to this, and finally directed to a photodetector.

In this case, the structure to be studied is a boundary wall of our laboratory, and also an integral part of the building.

Figure 1 shows the wall used in this evaluation. The wall has rectangular geometry: width (a = 4.51 m), height (b = 2.08 m) and thickness (t = 0.12 m). One can also distinguish the attached mirror on the wall, on which the laser beam falls and whose reflection is finally redirected to the photodetector.

Figure 1: Brick wall, object of the evaluation.

Results and Discussion

Theoretical approach

The theoretical approach that we apply in this work in order to understand the results, is the one developed by Herman Russell [2] for the case of vibration of rectangular membranes, where he concludes with a specific relation (1) for the possible vibration frequencies (f_{nm}).

$$f_{nm} = (c/2)\sqrt{(n/a)^2 + (m/b)^2} \qquad (1)$$

Where: n, m are integer values = 1,2,3,4...
a: width
b: height
c: sound speed

As will be seen later, this relationship will explain the results obtained, although not completely, so, it can be considered a first approximation to the correct theory.

Experimental

As is common in all our LPD evaluations [1], our ordinary procedure is to locate the approximate spectral location of the structure's first Eigen vibration mode using blows. Then, in a second stage, we proceed to apply sound waves to find by Resonance this and the different higher Eigen frequencies. However, on this occasion, we will begin the evaluation, taking into account a prior measurement, the natural movement of the wall, whereby the wall is not perturbed intentionally at all, however, the reflected ray contains information about the spontaneous vibrations of the same, usually produced by the environment (traffic, building movement), which, although imperceptible, since they are signals that border on background noise, can be measured by the LPD method. This measure will allow us to complement and justify our more direct evaluations.

Natural vibration

As a first experimental approach, we applied the LPD procedure to measure and evaluate the natural Wall vibration (without forced vibrations). Figure 2 shows a sector of the spontaneous wave, from which we can make a visual estimation of the predominant contribution, resulting in a vibration at approximately 29 Hz. Despite its sinusoidal deformation, an additional contribution of other vibrational components is presumed.

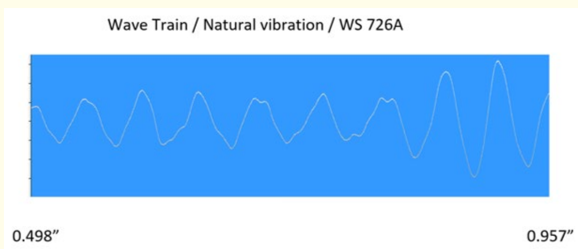

Figure 2: Partial wave train of the natural Wall vibration (WS726A).

However, as usual, the most appropriate evaluation of this wave is the FFT (Fast Fourier Transform) analysis, which is shown in Figure 3.

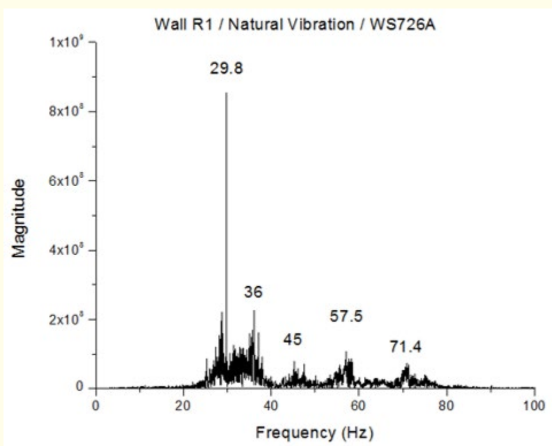

Figure 3: FFT spectral analysis of the wave train WS726A, obtained for the natural Wall vibration.

From the resulting spectrum (Figure 3) the predominant mode of 29.8 Hz is clearly identified, which was estimated earlier from the previous evaluation and which essentially corresponds to the fundamental vibration of the structure.

Furthermore, in the same spectrum, the presence of other secondary coexcited frequencies can also be identified, although to a lesser extent, which are summarized in Table 1, and to which we will refer later.

WS 726A	29.8	36	45	57.5	71.4

Table 1: Predominant Wall natural vibrations (Hz).

Excitement by Blows

As stated in previous works, the knocking procedure enables us to estimate the spectral position of the first vibration modes very accurately. If we lightly touch the structure, it will vibrate preferably in its first fundamental modes (Eigen frequencies).

The LPD measurement of the vibration produced in the Wall by Hammer strokes is presented in Figure 4.

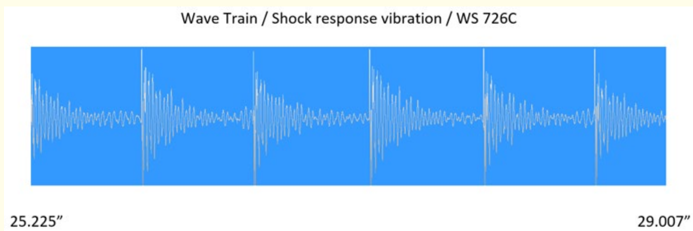

Figure 4: Partial wave train of the Wall vibration produced by blows (WS726C).

From the generated wave (Figure 4) we perform the respective FFT analysis and obtain the spectrum shown in Figure 5.

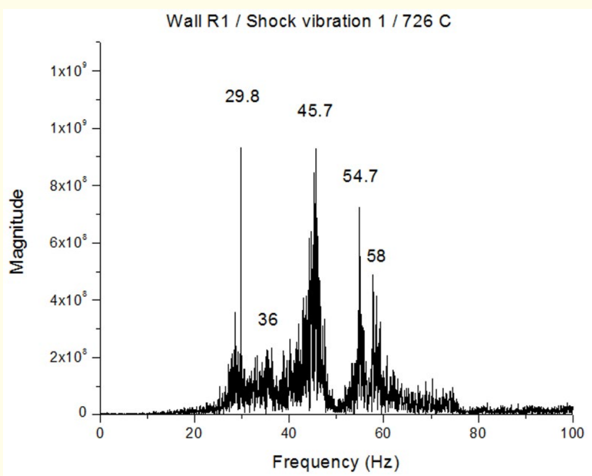

Figure 5: FFT spectral analysis of the wave train WS726C, obtained for the Wall subject to blows.

Again, in the spectrum (Figure 5), we can clearly identify the occurrence of peaks and relative maxima, which are summarized in Table 2.

WS 726C	29.8	36	45.7	54.7	58

Table 2: Predominant Wall vibrations (Hz), activated by shocks.

As can be seen, both modalities (natural and excitation by blows) give us partially, the same principal vibrations, and also peaks of non-common frequencies, which will later be proven to constitute in fact complementary Eigen frequencies of the structure. This will be confirmed next by the Resonance Evaluations.

Excitement by sound waves

As stated previously, sound excitation and the LPD detection method allow us to accurately find the structure's natural frequencies by tuning the acoustic signal to some frequency inherent to the structure (Resonance Effect), where the amplitude of the vibration response is significantly amplified, allowing the corresponding natural frequency (Eigen) to be fully identified.

This tuning task has been carried out manually up to now, and it is main characteristic is, to observe the LPD response on the PC screen; when approaching a Resonance, the signal goes from an insignificant background noise to a signal of much greater amplitude, usually sinusoidal, at which point we suspend the tuning and take the opportunity to record the response and be able to analyze it.

As indicated, typically the LPD response at resonance is a sinusoidal wave (of a defined frequency), however if several resonant frequencies are excited at the same time, a predominant component superimposed by secondary modulations of lower amplitude will appear.

Regarding the wall, we want to highlight here one specific case: The first resonance vibration.

First Resonance: f_0 = 29 Hz.

Figure 6 shows a section of the waveform resulting from tuning to the first resonance (29 Hz). As can be seen, a quasi-sinusoidal principal component of 29 Hz predominates.

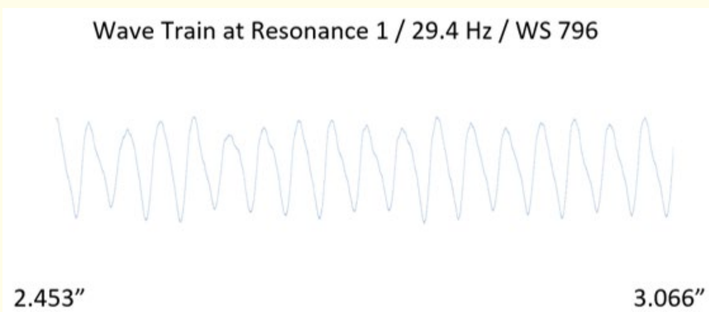

Figure 6: Partial wave train of the Wall vibration produced at the first Resonance (29.4 Hz) (WS796).

Applying an FFT (Fast Fourier Transform) spectral analysis to this signal, we obtain the spectrum in figure 7.

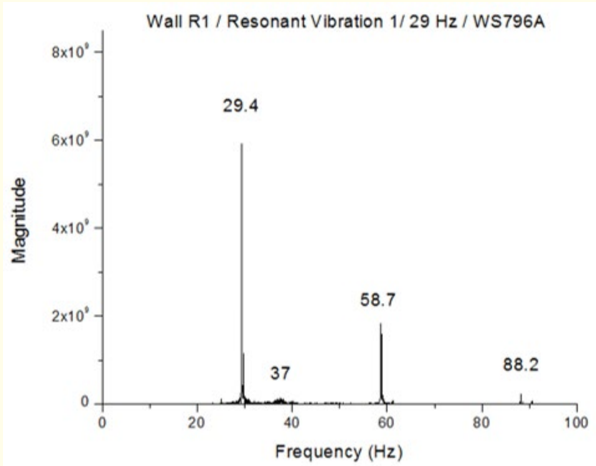

Figure 7: FFT spectral analysis of the wave train of Figure 6, for the Wall at first Resonance.

The spectral result of Figure 7, allows us to clearly identify the fundamental vibration mode f_0 = 29.4 Hz: Mode (1,1) and the secondary modes: 37 Hz: Mode (2.1), 58.7 Hz: Mode (2,2), 88.2 Hz: Mode (3,3).

First Ten Resonances

The results of evaluating the first 10 Wall Resonances are presented in summary in Table 3, and the complementary (FFT Spectra) in what follows (Figures 8 to 16). Table 3 essentially highlights the values (column red) of the effective resonances obtained.

Modes	***Faktor*** $\sqrt{(n)^2+(2.168m)^2}$	***Natural Modes (Hz)***	***Blow Modes (Hz)***	***Experimental Resonant Modes (Hz)***	***Faktor*** f_o	***Theoretical fitting (Hz)***
(1,1)	2.39	29.8	29.8	29.4	12.3	29.4
(2,1)	2.95	36	36	37.3	12.6	36.3
(3,1)	3.70	45	45.7	45.2	12.2	45.5
(1,2)	4.45		54.7	54.6	12.3	54.7
(4,1)	4.55			56	12.3	55.9
(2,2)	4.78	57.5	58	58.3	12.2	58.7
(3,2)	5.27			64.8	12.3	64.8
(5,1)	5.45			68.1	12.5	67.0
(4,2)	5.90	71.4		71.3	12.1	72.5
(6,1)	6.38			78.0	12.2	78.4
				Average	12.3	

Table 3: Experimental Results and Theoretical Approach.

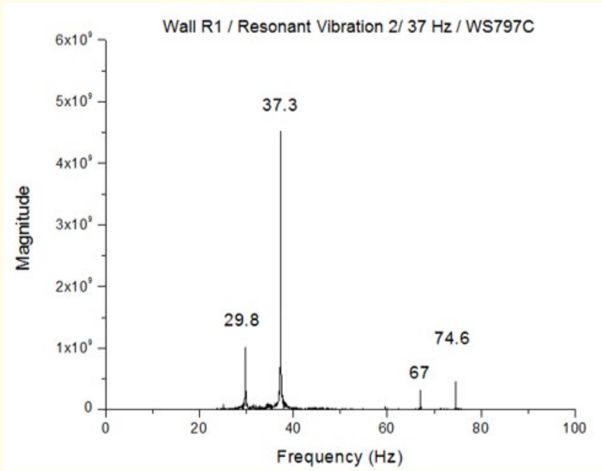

Figure 8: FFT spectral analysis of the wave train obtained for the Wall at the second Resonance.

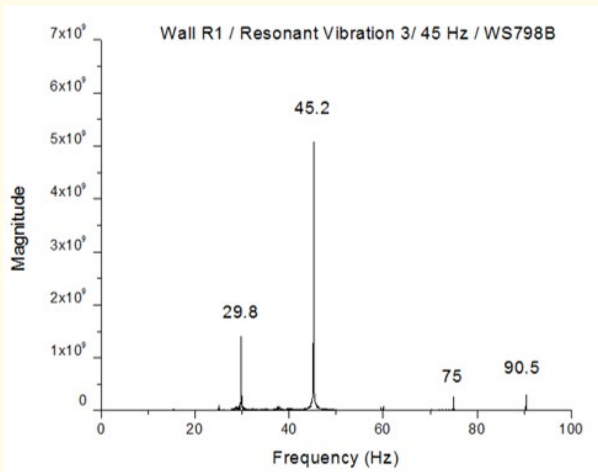

Figure 9: FFT spectral analysis of the wave train obtained for the Wall at the third Resonance.

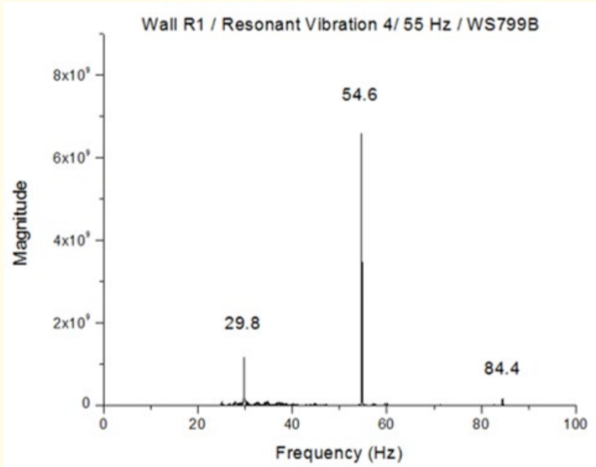

Figure 10: FFT spectral analysis of the wave train obtained for the Wall at the fourth Resonance.

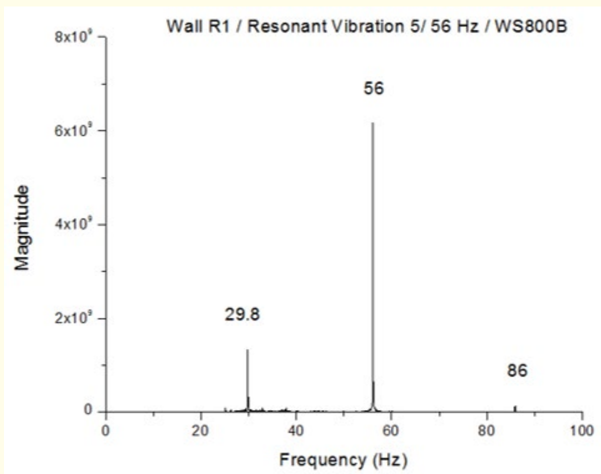

Figure 11: FFT spectral analysis of the wave train obtained for the Wall at the fifth Resonance.

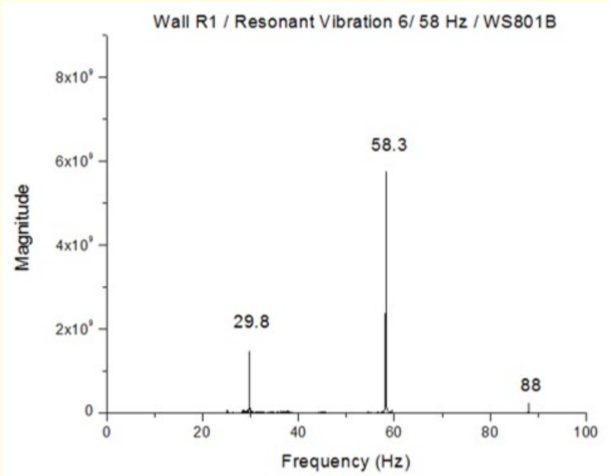

Figure 12: FFT spectral analysis of the wave train obtained for the Wall at the sixth Resonance.

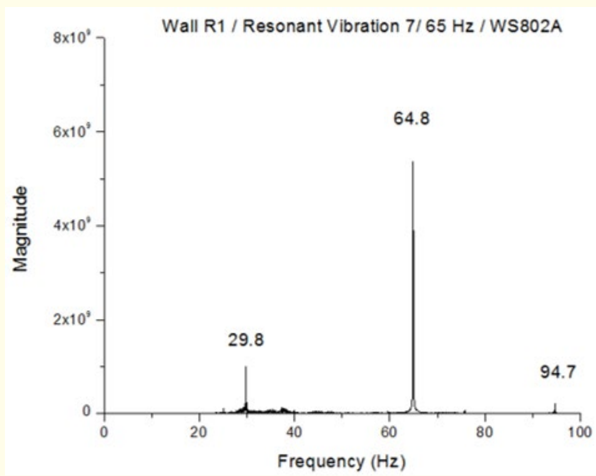

Figure 13: FFT spectral analysis of the wave train obtained for the Wall at the seventh Resonance.

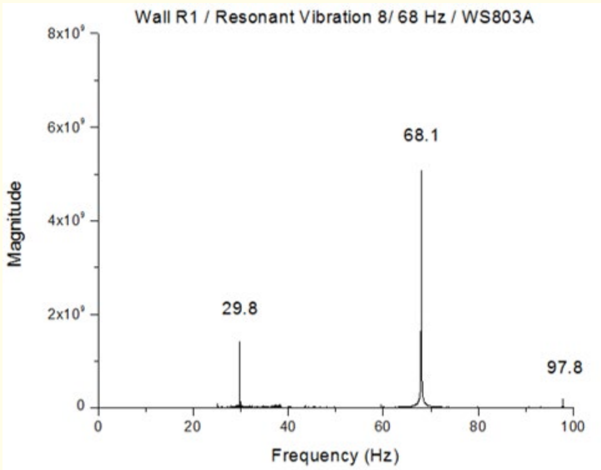

Figure 14: FFT spectral analysis of the wave train obtained for the Wall at the eighth Resonance.

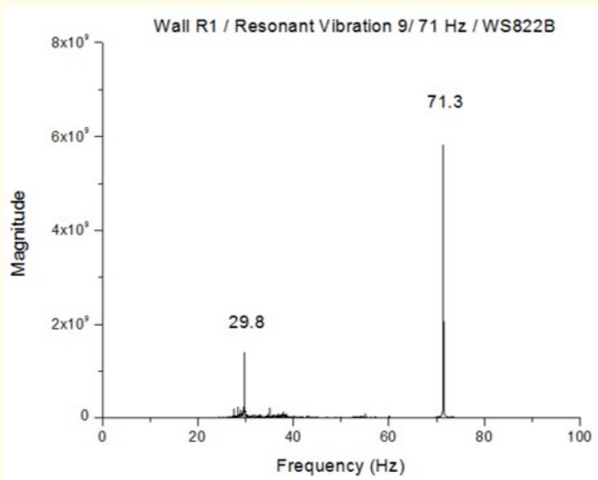

Figure 15: FFT spectral analysis of the wave train obtained for the Wall at the ninth Resonance.

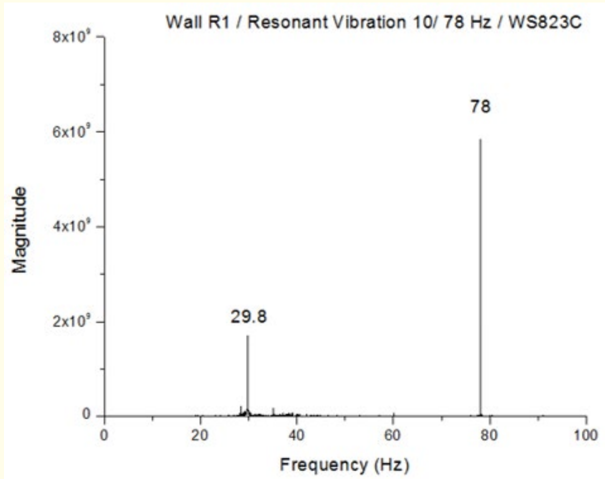

Figure 16: FFT spectral analysis of the wave train obtained for the Wall at the tenth Resonance.

Discussion

A fundamental aspect in the analysis of the obtained results is to note the fact, that the initial measurements (natural vibrations, vibrations due to impact) constitute a quasi-instantaneous measurement of the first Eigen vibrations of the structure. Therefore, if we take this as a reference, we can estimate the generation pattern of these data.

In this sense, we observe that a relation of the form; can explain the sequence of these Eigen frequencies:

$$f_{nm} = f_0\sqrt{(\boldsymbol{n})^2 + (\boldsymbol{2.168m})^2} \qquad (2)$$

Where, f_0= c/2a and the assignment of parameters (n,m) would be the one indicated in Table 3.

This relation (2) is essentially relation (1), explained above, when: (a = 4.51 m) and (b = 2.08 m).

Where a is the width of the rectangular Wall and c is the speed of sound in the medium (Wall), c= $\sqrt{E/\rho}$.

If we consider that the Wall is built of Bricks ($E = 1.4 \times 10^{10}$ N/m^2, $\rho = 1.08 \times 10^3$ kg/m^3), then the value of the constant f_0 should be f_0 = 399 s^{-1}, which differs significantly from the value found experimentally (f_0 = 12.3 s^{-1}).

As can be seen, Russell's theory [5] only explains the results qualitatively, but not quantitatively, which was to be expected since that theory corresponds to membranes.

However, the confirmation of the validity of relation 2 is definitively given by the good correlation with the effective resonant frequencies of the Wall (red row), of which the first 10 are presented in Table 3. The corresponding values (n, m) that justify them are also included, satisfying very well with the "theoretical fitting" exposed.

Regarding the LPD method, it is worth reiterating its high sensitivity. As demonstrated in this work, even without forcing the structure to vibrate, it is capable of detecting the structure's Eigen vibrations, signals that are usually drowned out by the background noise of the response.

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