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Application of the LPD (Laser Photo Deflection) Method to the Vibrational Diagnosis of a Concrete Beam

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Abstract

This work presents the optical evaluation of the vibrational behavior of a concrete beam using an unconventional optoacoustic procedure, the LPD method. In this case, the beam is an integral part of our laboratory construction in Lima; it supports part of the laboratory roof. Using our procedure, we experimentally determined the first 10 Eigen frequencies (14.4 Hz, 40 Hz, 78 Hz, etc.) of the beam, which we can explain using simple cantilever theory.

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

Introduction

The topic of structural diagnosis is of great relevance for countries like Peru, especially because they are located in a highly seismic zone. Civil engineering currently has diagnostic devices based mainly on electromechanical sensors (accelerometers), which are effective but have certain limitations (size, sensitive frequency range, measurement speed).

In this regard, we must highlight that there are indeed modern optical methods (interferometry, Laser Doppler Vibrometry (LDV)) that allow structural vibrations to be measured with great precision, however the lack of massive applications points to a probable high cost or immaturity of the technique.

In this context, the LPD method applied by our group does not constitute a sophisticated equipment at all; it is essentially based on three elements: a laser, a mirror, and a photometric detector. We have not found any current antecedents to this application, however, we do find a closely related historical reference: the *photo phone* [1]. In 1880, the famous inventor Alexander Graham Bell presented his relevant invention, which allowed speech transmission on a beam of light (sunlight). However, actually with the use of Laser and existing technological support, it is possible to detect vibrations, even as sensitive as those generated in a room by the voices produced inside. Initially, our main objective was to apply the LPD method to study vibrations in a building and in fact we managed to make our building vibrate with sound and optically detect the vibrations produced [2]. However, the complexity of the data obtained did not allow us to understand completely the obtained results. Even applying the most current structural evaluation programs (ETABS, SAP2000, e.g.).

Understanding that the vibration of a building involves all of its partial vibrations (walls, columns, beams) on the whole, led us to study sequentially the individual responses of a building's components using the LPD method. In this case, we limit ourselves to presenting the results obtained on a concrete beam.

Materials and Methods

The method applied by our group in the evaluation of the vibrations of a structure, in this case a concrete beam, is the LPD Method (Laser Photo Deflection), by which the reflection of a laser beam on a mirror attached to the structure, will transmit and amplify its vibrations, which are finally detected by a photometric sensor.

As is common in all our LPD evaluations, we initially locate using blows the spectral position of the first proper mode of vibration of the structure, and then in a second stage, we proceed to apply sound waves to find by Resonance the possible Eigen frequencies.

Theoretical basis

The theoretical justification of the experimental results obtained in this work is carried out using cantilever theory [3]. For the case of a beam fixed at both ends, cantilever theory provides a solution for the vibrational modes inherent to the bar, the relation (1):

$$f_n = \frac{\alpha_n^2}{2\pi}\sqrt{\frac{EI}{\rho A L^4}} \qquad (1)$$

Where: α_n = 4.73, 7.85, 11.0, 14.14…
E is Young's modulus of the material,
I is the moment of inertia,
ρ is the density of the material
L is the length of the bar
A the cross section of the bar

Experimental Setup

Figure 1 shows the experimental arrangement used in this evaluation. One can clearly distinguish the concrete beam evaluated and which partially supports the roof of the Laboratory. Figure 1 also shows the position of the laser used, the mirror, and the photometric detector, resulting in an effective distance of almost 7 meters.

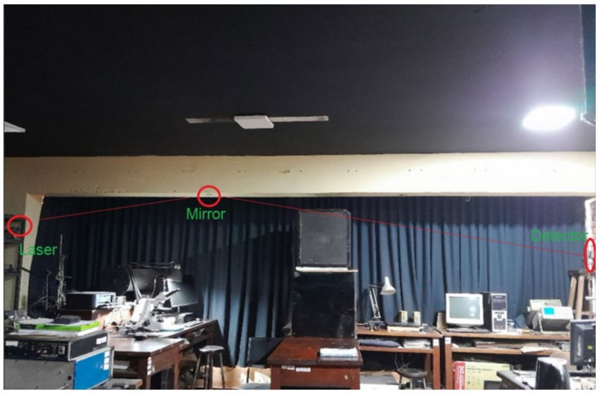

Figure 1: Experimental LPD arrangement: The optical vibrational evaluation of a concrete Beam.

Results and Discussion

As is common in all our LPD evaluations [4], we initially locate the approximate spectral location of the structure's first natural vibration mode by means of blows, and then in a second stage we proceed to apply sound waves to find the different higher natural frequencies by Resonance.

Excitement by Blows

As stated in previous works, the knocking procedure allows us to identify the approximate spectral position of the first vibration mode. If we lightly touch the structure, this will vibrate preferably in the first basic modes (Eigen frequencies).

The LPD measurement of the Beam vibration produced with Hammer strokes is presented in Figure 2 and Figure 3.

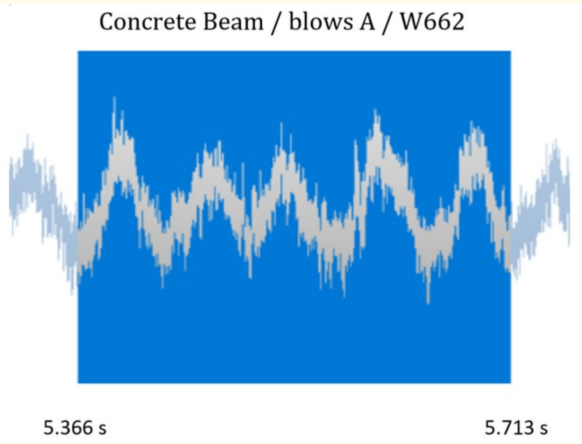

Figure 2: First LPD wave train, resulting from lightly touching the Beam sequentially (around the center of the beam).

Partial analysis of the wave pattern shown in Figure 2 gives an approximate frequency of 14.4 Hz.

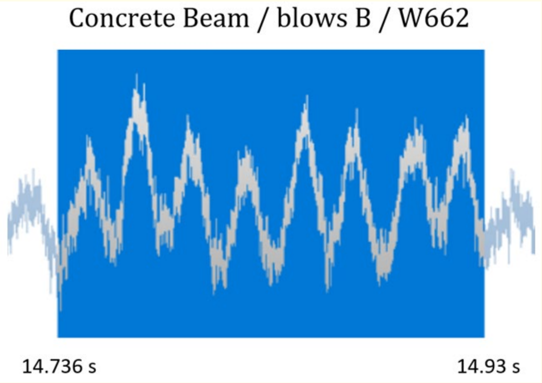

Figure 3: Second LPD wave train, resulting from lightly touching the Beam sequentially (about 1/4 of the beam).

Partial analysis of the wave pattern shown in Figure 3 gives an approximate frequency of 41 Hz.

An FFT (Fast Fourier Transform) spectral analysis of the indicated wave trains gives the spectrum shown in Figures 4 and 5, where the most precise value of those oscillations can be seen to be located at 14.5 Hz and 40.5 Hz, respectively.

This frequencies correspond basically to the first proper mode (Mode 1) and the second proper mode (Mode 2) of vibration of the beam, as can be correlated next with the theory.

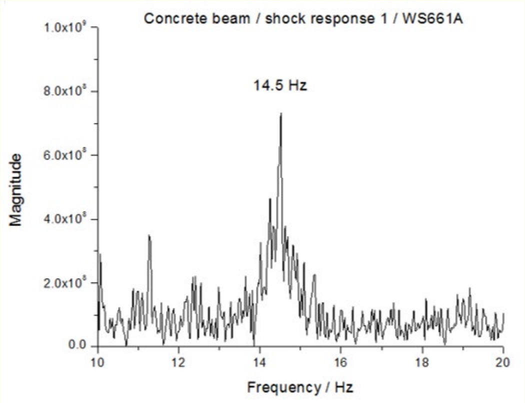

Figure 4: FFT spectral analysis of the wave train of Figure 2.

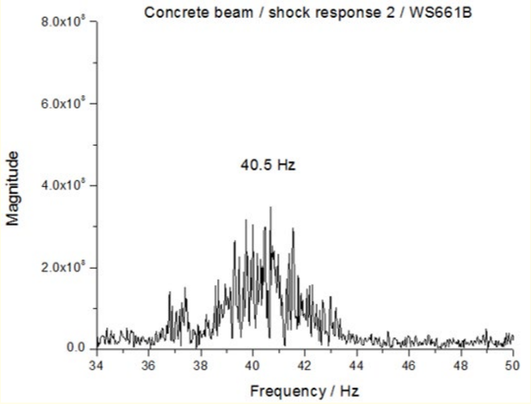

Figure 5: FFT spectral analysis of the wave train of Figure 3.

Excitement by sound waves

After having approximately located the spectral position of the beam's first two vibration modes, we proceed to subject the bar to sound waves, first tuning to around 14.5 Hz. Manually finding a maximum response around 14.4 Hz due to the resonance effect. Figure 6 shows part of the resulting wave.

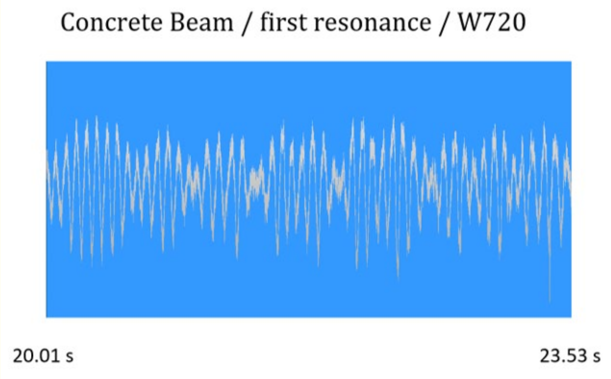

Figure 6: LPD Wave train resulting from exciting the concrete Beam around the first resonance Mode (14.4 Hz).

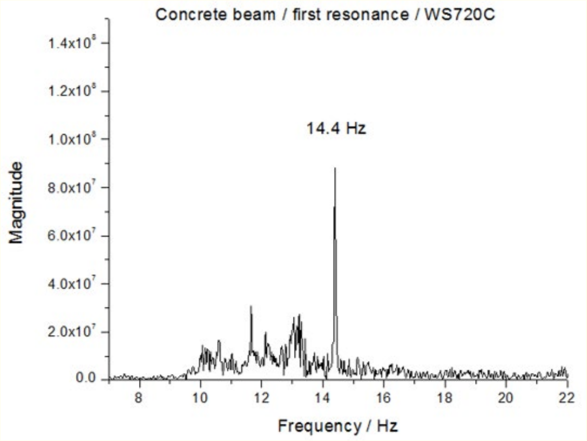

Figure 7: FFT spectral analysis of the wave train of Figure 6. Around the first resonance peak.

Figure 7 finally shows the FFT evaluation of the wave train in Figure 6, giving a value of 14.4 Hz.

Following the same procedure, we find the higher resonant frequencies (in total 10), which are explicitly detailed in Table 1 (Experimental Data), and whose FFT spectra are also shown below (Figures 8 to 16).

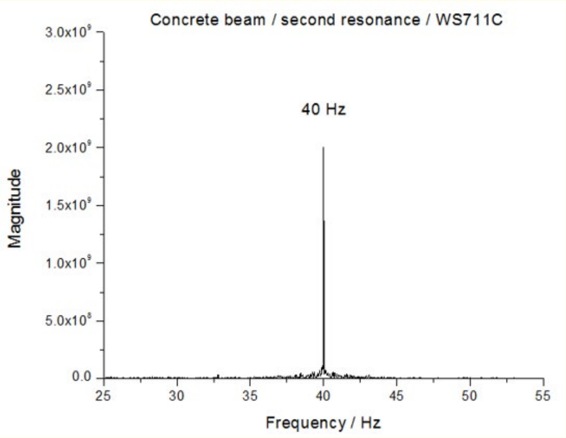

Figure 8: FFT spectral analysis of the wave train obtained around the second resonance peak.

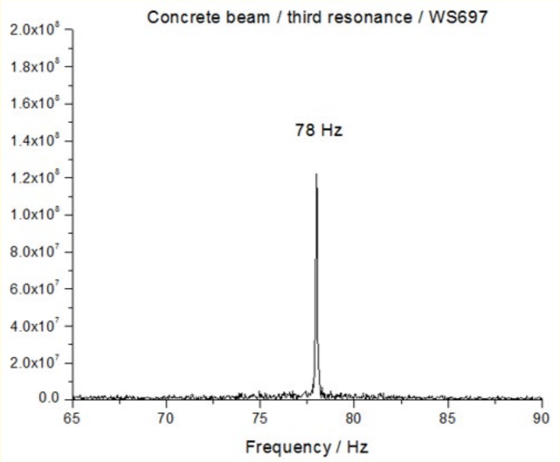

Figure 9: FFT spectral analysis of the wave train obtained around the third resonance peak.

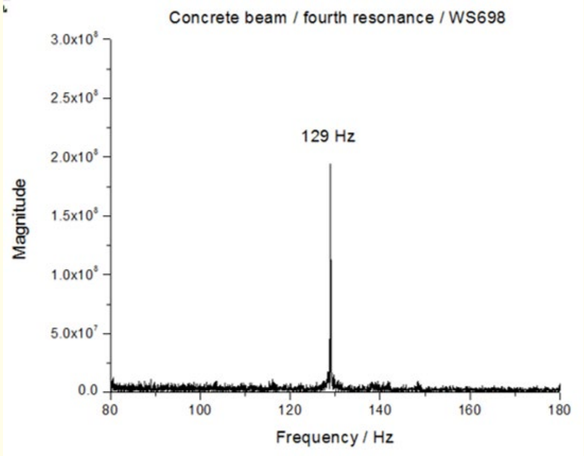

Figure 10: FFT spectral analysis of the wave train obtained around the fourth resonance peak.

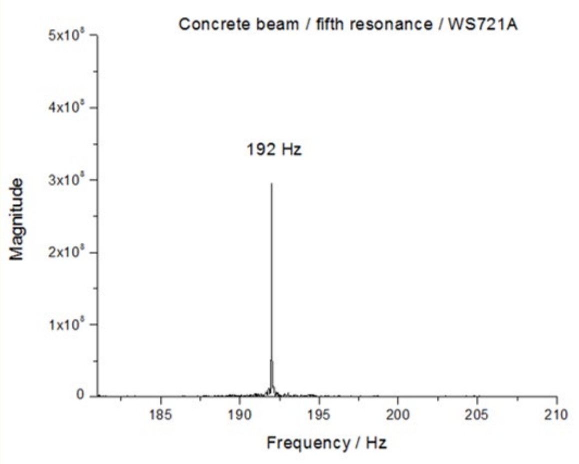

Figure 11: FFT spectral analysis of the wave train obtained around the fifth resonance peak.

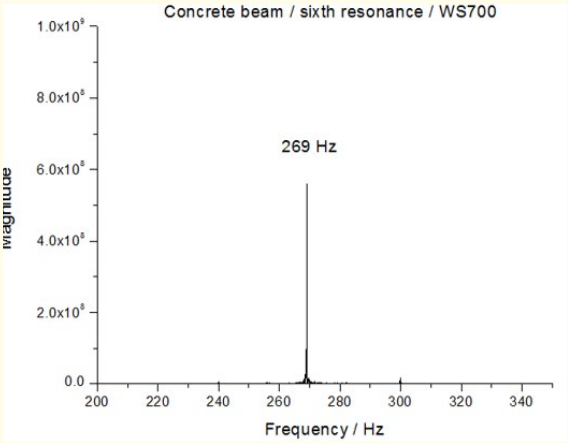

Figure 12: FFT spectral analysis of the wave train obtained around the sixth resonance peak.

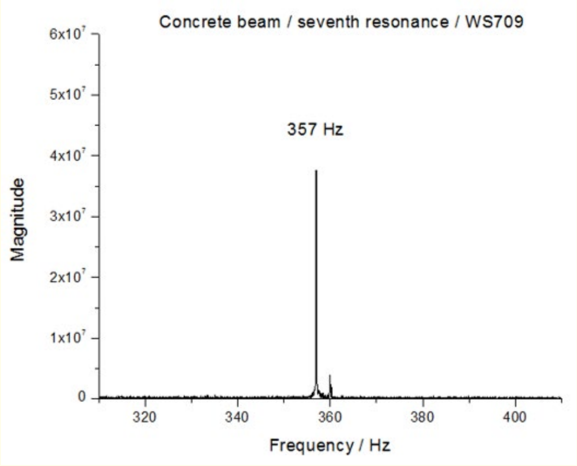

Figure 13: FFT spectral analysis of the wave train obtained around the seventh resonance peak.

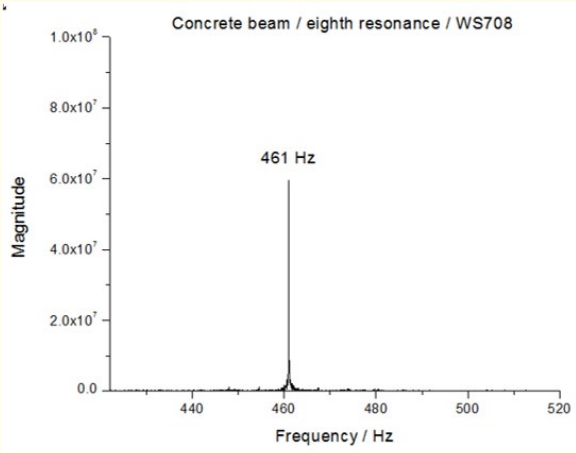

Figure 14: FFT spectral analysis of the wave train obtained around the eighth resonance peak.

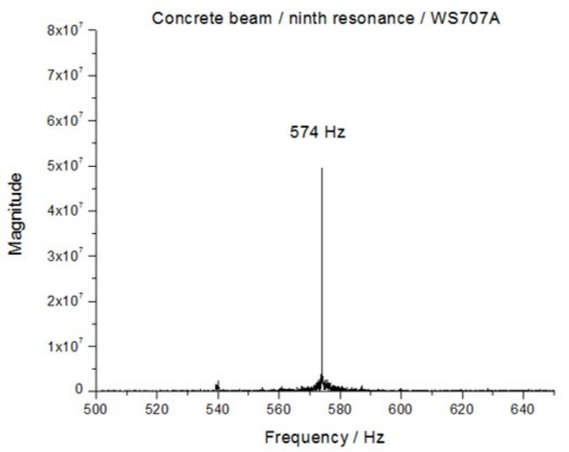

Figure 15: FFT spectral analysis of the wave train obtained around the ninth resonance peak.

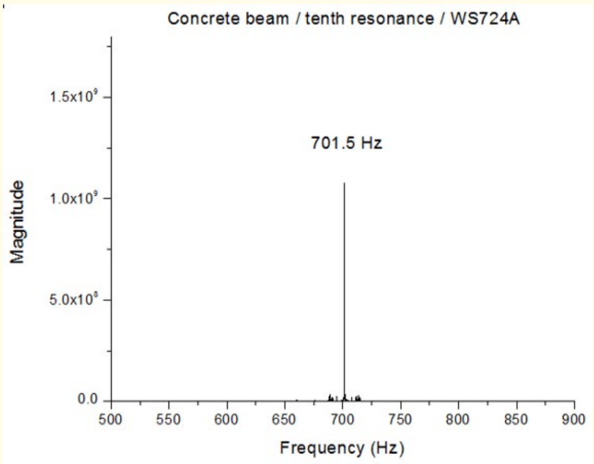

Figure 16: FFT spectral analysis of the wave train obtained around the tenth resonance peak.

Mode	Experimental Resonance frequencies (Hz)	Common factor K_n (Hz)	Theoretical approach (Hz)
1	14.4	4.04	14.4
2	40	4.08	39.8
3	78	4.05	77.9
4	129	4.06	128.8
5	192	4.04	192.4
6	269	4.05	268.8
7	357	4.04	357.8
8	461	4.06	459.6
9	574	4.05	574.1
10	702	4.05	701.5
…………..	………………	………………	……………..
Average		4.05	

Table 1: Experimental Results and Theoretical approach.

Discussion

To justify the obtained results, we apply the aforementioned theory of the cantilever and in particular, the relationship (1), for which we define a factor k_n, that should be a constant ($k_n \equiv f_n \,/\, (\frac{\alpha_n{}^2}{2\pi})$), if both the measured frequency and the assigned order are correct.

In Table 1 are indicated the resulting experimental k_n factors, observing a good correlation at all and obtaining an average value k_{ex} = 4.05, With this estimated value we obtain the most accurate theoretical values, which are indicated also in Table 1 and as can be seen agreed very well with the obtained experimental resonant values.

Even more, If we introduce the measurable geometrical values of the Beam: L = 6.615 m, b = 0.43 m, a = 0.30 m, and the reference value of the Beam material (supposed to be concrete) [5], such as the density $\rho = 2.3 \times 10^3$ kg/m^3 and Young Modulus $E = 2.5 \times 10^{10}$ N/m^2, to obtain the corresponding theoretical value k_t, we obtain: $k_t = 6.57$, which differs somewhat from the value obtained experimentally: $k_{ex} = 4.05$.

This discrepancy was expected from the start, because it is not about a free beam, but, as can be seen from Figure 1, it is part of the roof structure. Furthermore, it is not just a concrete structure alone, but it is also supposed to have a metal frame incorporated, which gives it consistency.

What has been a surprise for us, is finding out that the measured resonances largely coincide with those expected for a free beam (cantilever theory).

Conclusion

The widely positive result obtained in this evaluation confirms the potential of the LPD Method in the evaluation of defined structures (building components).

However, for this and other similar works, to have the appropriate scientific consistency, it is necessary to carry out evaluations on individual devices, of which all their properties are previously known, so that the results are not subject to approximations or interpretations, which is a task that we have ahead of us.

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