DETECTION OF BUILDING VIBRATIONS APPLIYNG LASER PHOTO DEFLECTION RESPONSE

SISTEMA DE EVALUACION DE EDIFICIOS POR MEDIO DE MEDICIONES LASER DE FOTO-DEFLECCION

Aníbal Valera[1], Edward Romero[2], José Florindez[3]

RESUMEN

En este trabajo se presenta el resultado de evaluar las vibraciones de un Edificio (Pabellón de Ciencias / UNI) en base al Método de Foto Deflexión Láser. Las vibraciones evaluadas del edificio son respectivamente de naturaleza espontánea (producidas por el viento, trafico automotriz, ondas sísmicas) e inducidas (micro vibraciones producidas por excitación sonora). El procedimiento permitió evaluar los siguientes casos: A- Efecto Resonante producido en el pasadizo principal del edificio, B- Correlación de vibraciones espontáneas e inducidas en el edificio, C- Detección y evaluación de la vibración del Edificio generada por una onda Sísmica.

Palabras clave.- *Vibraciones de estructuras, Ondas sísmicas, Detección láser, Foto deflexión.*

ABSTRACT

This paper presents the results of evaluating the vibration of a Building (Science Building / UNI) based on the Method of Laser Photo deflection. The evaluated vibrations of the building were, respectively, of spontaneous nature (produced by wind, automobile traffic, seismic waves) and induced (micro vibrations excited by sound waves). The procedure allowed us to evaluate the following cases: a-A resonant effect occurred in the principal building Hall, b-Correlation of spontaneous and induced vibrations in the building, c-Detection and evaluation of building vibrations generated by Seismic waves.

Key words.- *Building vibrations, Seismic waves, Laser detection, Photo deflection.*

INTRODUCTION

Free vibration analysis plays an important role in the structural design of buildings, especially for the first modes because the first modes shape is a dominant component in wind- and earthquake-induced vibrations. Many researchers in structural engineering have devoted to obtain accurate experimental and theoretical results for the free vibration of buildings in the past decades.

Knowledge of the behavior of civil structures under seismic excitation is of great interest in earthquake-prone areas. For this reason many countries have equipped some buildings with instruments and monitor them continuously in order to record possible structural responses to earthquakes. Prior to the occurrence of an earthquake, it is important to identify the parameters governing the dynamic behavior of the building, natural frequencies and mode shapes. This information is usually obtained by means of forced or ambient vibration tests using modal identification techniques [1–5]. The above data are important per se, but can provide more meaningful results if they are used to update a theoretical model of the building, which is potentially

---

[1]Dr. Docente investigador de la Facultad de Ciencias de la Universidad Nacional de Ingeniería, [2]Egresado de la Facultad de Ciencias de la Universidad Nacional de Ingeniería, en la especialidad de Física, [3]Estudiante egresado de la Facultad de Ciencias de la UNI, en la especialidad de Física.

able to estimate important mechanical properties, such as the elastic moduli of structural elements and boundary conditions [6–10].

The dynamic response of structures depends on the frequency characteristics of the excitations. Over the years, the study of building response under damaging ground vibration conditions has been earthquake-oriented because of the great economic and social impact a major earthquake can produce. Another reason behind this concerns the nature of vibrations: earthquake excitations occur at relatively low frequencies, and low-frequency excitations have greater energy than high-frequency excitations, posing greater destructive effects.

While the above notion is true in a general sense, high-frequency ground motions (referred to as "ground shocks" hereinafter) of potentially damaging magnitude can occur as a result of construction blasting; piling; mining; and at the severest, of accidental detonation of surface or underground ammunition storage magazines.

Actually, most of the experience gained in the evaluation of building dynamical response resumes to empirical rules, obtained from observed damage and recorded peak excitations. The exact response phenomenon and the underlying mechanisms for this special category of structural dynamic problems remain unclear, demanding more and accurate data. This faces one of the main difficult in this study, which is the limitation on precise instrumentation

In a recent work performed for our group [11 y 12], we demonstrated the effectiveness of the "Laser Photo Deflection" (LPD) Method in the characterization of simple structure vibrations (Walls, Roof).

In this work we begin to study Building vibrations via LPD measurements, confirming the feasibility and high accuracy of the optical process.

EXPERIMENTAL

The laser photo deflection system

Fig. 1 presents the Laser Photo Deflection System applied to the generation and detection of structural vibrations. The acoustic System (2500 W) shown schematically, allows an effective excitation of vibrations up 10 Hz.

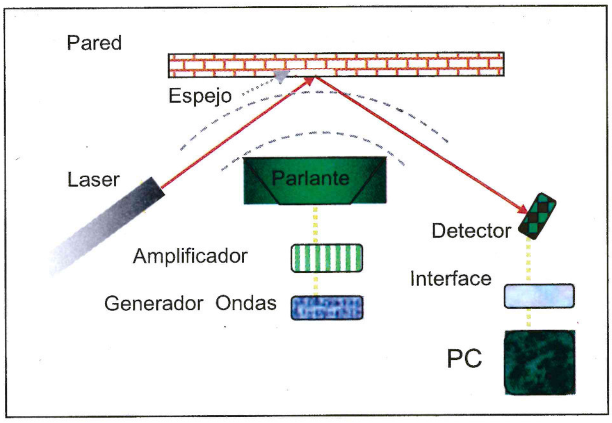

Fig. 1 *Generation and Detection of vibrations of structures, via sound and Laser Photo Deflection measurements respectively.*

The acoustic wave produce a micro vibration of the structure (per example a Wall in Fig.1), which modulates synchronic the direction of the reflected Laser ray. The Deflected modulation is detected by a LPD Sensor and the data transferred to a PC for Recording and Evaluation.

The laser photo deflection detector

The optical detection system must be adapted to new working conditions (External), since previous work was realized only at labor distances.

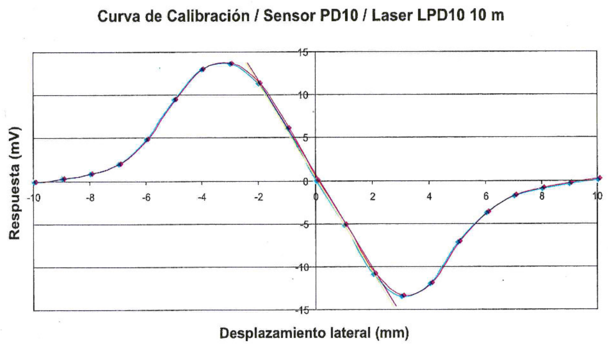

Fig. 2 *Calibration curve of Laser Photo Deflection Sensor* ***PD10 (Laser LPD10, 10 m)****. The red line indicates the effective linear range of the sensor (± 2 mm/ lateral maximum deviation).*

The optical path for the beam (laser) to the sensor is now significantly higher (about 10 m) and subject to weather conditions. For this purpose, we designed and built the deflection detector **PD10** (to be patented next), whose characteristic calibration curve is shown in Fig. 2.

Vibration measurements

Fig. 3 shows an overview of the Science Building (Pabellón R / UNI Campus), where our vibration measurements were performed. The building is a 4 story, steel frame with masonry.

In order to acquire experience with the multiple vibrations of a Building, a series of evaluations were conducted in three zones of the building.

Main corridor resonance

The main corridor of the building is a passage located at the first floor under the red doted zone shown in Fig.3.

A singular effect takes place along this corridor, when an air extractor located nearly is turn on: a standing wave is excited. The resounding effect is clearly perceived by a person when this walks along the floor:

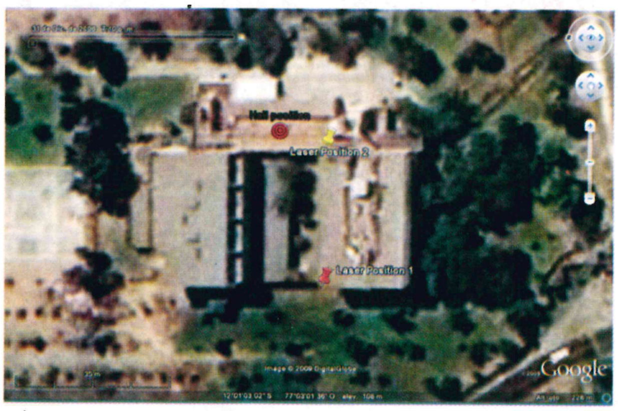

Fig. 3 *Building of Science (Overview), showing the positions, where evaluations were done: Red dot (Main Corridor), yellow pointer (Structure vibration A), red pointer (Structure vibration B).*

Fig.4 schematics the observation: Along the corridor there are positions, where a person feels clearly an earthquake sound effect (anti nodes) and other positions, where no vibration at all is perceived (Nodes).

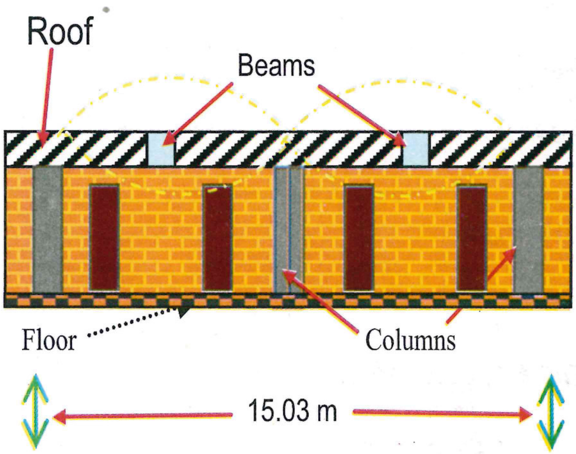

Fig. 4 *Schematic view of a section of the main corridor (1st floor, R Building), where the details of the induced wave (stationary Wave) are located. The Nodal position coincides with the Columns positions and the Anti nodal position with the Roof beams positions.*

Fig. 4 shows schematically a section of the corridor and the details of the generated wave: The Nodal position coincides with the Columns positions and the Anti nodal position with the Roof beams positions From the observation alone, one can not conclude what is vibrating all along the corridor (approximately 35m) (floor, ceiling, etc.). However, the occurrence of nodes in the positions of the columns suggests that the structure self is vibrating.

A first step in the Resonance evaluation is to perform an analysis of the sound signal that accompanies the perturbation in anti nodal positions, which is shown in Figure 5. This shows clearly the occurrence of vibration peak about 28 Hz, which corresponds to the observed longitudinal proper resonance. In order to complement the observation, we measure also direct at the air extractor the produced vibrations (sound analysis), the result is shown in figure 6, from the spectral decomposition, we can confirm the occurrence of a strong vibration also at a frequency of 28.3 Hz, which coincides with the resonance detected far away from this position (aprox. 35 m).

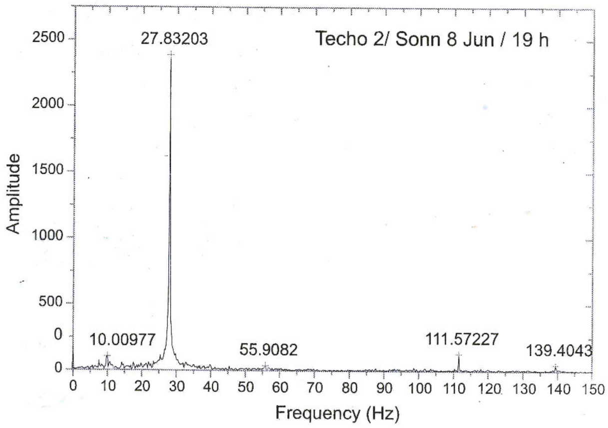

Fig. 5 *Spectral Analysis (FFT) of the sound signal associated with the vibration detected in the corridor.*

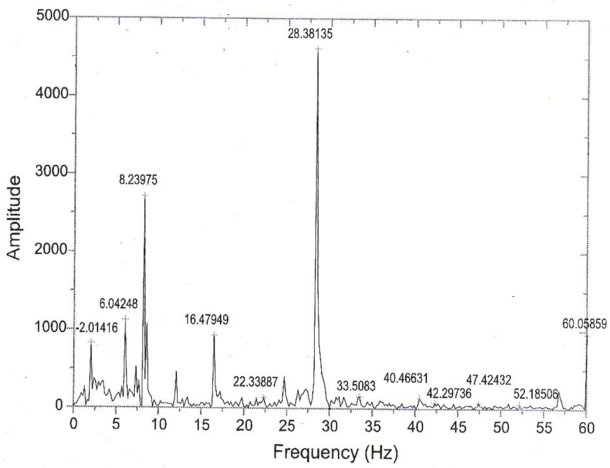

Fig. 6 *Spectral Analysis (FFT) of the noise captured directly from the extractor that produces the resonant vibration.*

An additional important observation that can be inferred from the spectrum of Figure 5, is the fact of the simultaneous occurrence of other minor resonant vibrations that take place together with the strong resonance ($v_0 = 27.8$ Hz), such as 55.9 Hz ($2v_0$), 111.6 Hz ($4v_0$) and 139.4 Hz ($5v_0$), which corresponds to the harmonic vibrations of the fundamental frequency (v_0), that are simultaneous excited. This fact must be worked out experimentally in order to confirm it at all. The occurrence of these simple harmonic vibrations is an indicator of the validity, for this case, of the one dimension Wave Model, as the corresponding theoretical Model.

As a complement to the described evaluations on the corridor, we performed also LPD (Laser Photo Deflection) measurements. Fig. 7 shows a schematic view of the applied experimental arrangement: The vibration sensing element is located under a beam at the roof of the passage. The sound box (excitator) was located on the floor facing to the wall. Both positions (from sensor and excitator) correspond to anti nodal zones. What we expected to obtain with this evaluation was the excitation of the 28 Hz Resonance. Nevertheless what we obtained were two little resonances: one around 14 Hz and the other centered at 40 Hz, which are very likely to be related to the adjacent wall and floor respectively, as the speaker driver was in direct contact with them. This negative result reinforces the supposition that the observed resonance (28 Hz) is generated by the movement of the structure self with no mayor influence of floor or walls. In a next evaluation Program, we will excite direct the structure to prove these assumptions.

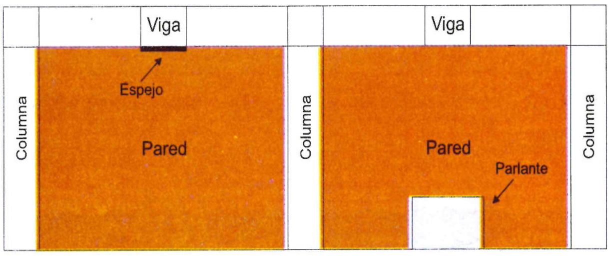

Fig. 7 *Schematic diagram of the experimental arrangement used to make the first Laser Photo Deflection measurements on the corridor (Internal Report JFTpI).*

Structure vibration A

Performing the previous evaluation Case 3.1, it was noticed that certain sound frequencies produced in the corridor (on the first floor), produced also a very sensitive vibration in the upper stages, resembling the occurrence of an earthquake. This observation leads us to realize a specific experiment: A vertical Laser Photo Deflection measurement.

Fig. 8 shows schematically the conceived vertical LPD setup. At the first floor (in the corridor), we located a Sound emitter (Box) facing to a mayor column and the Laser source. At an upper level (third floor) is located the LPD Detector. A yellow pointer in Fig.3 (Building over view) indicates the exact position of the vertical arrangement.

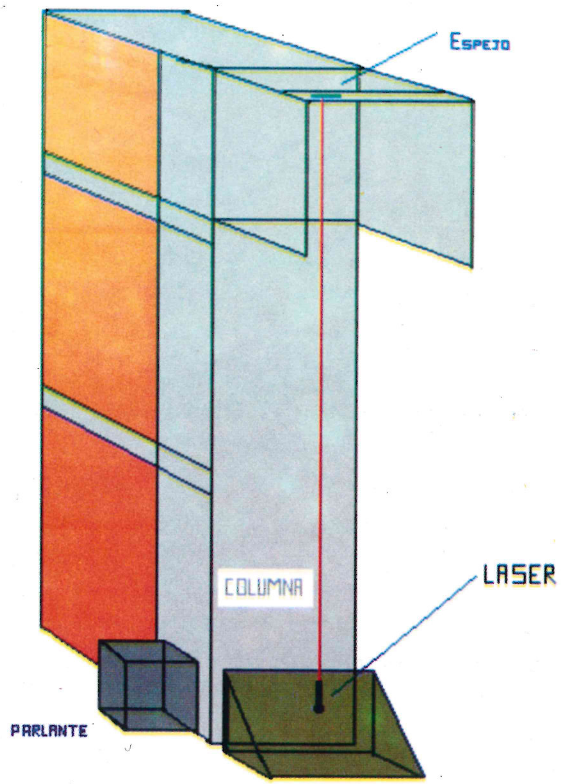

Fig. 8 *Schematic diagram for the vertical Laser Photo Deflection measurement LPD C3.2 from a lateral view (JFTpI Internal Report).*

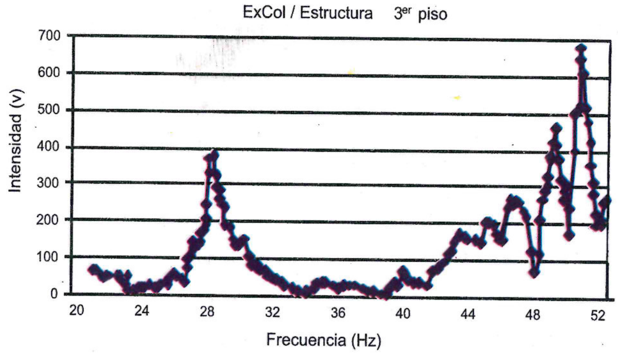

Fig. 9 *LPD spectrum of the vibration generated in the 3rd floor when the sound excitation is produced near a mayor column at the first floor.*

The result of the LPD vertical measurement is presented in the spectrum of Figure 9. This clearly shows the occurrence of a peak resonance around 28 Hz, which is coincidentally the frequency that produces also the longitudinal resonance described in section 3.1, this coincidence and the overall frequency response of the building, must be deeper studied in a next Project, in order to establish clear the corresponding Modal structure vibration.

Structure vibration B

The sector B of the Building **R** is the sector that houses essentially the laboratories (physical and chemical) and constitutes a 4-story structure with basement. The position of the optical sensor for all following evaluations was in a corner of the roof (fourth floor), similar to that described in Figure 8 (red pointer locator in Fig.3).

Evaluation of spontaneous vibrations.

The sensitivity of the optical sensor attached to the building is surprisingly high, it can clearly capture the movements induced by various.

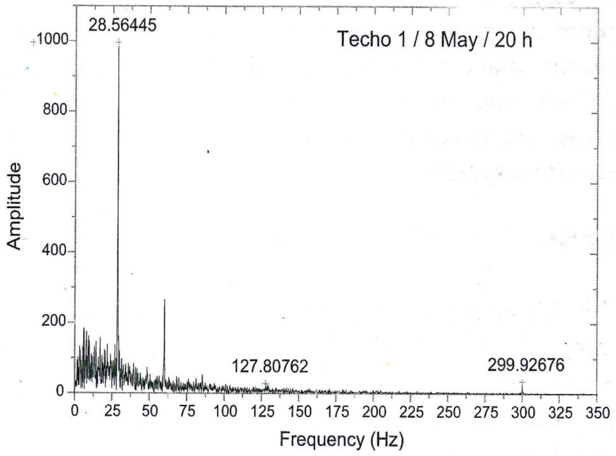

Fig. 10 *Spectral evaluation (FFT analysis) of the LPD signal from sensor B located on the roof of the building.*

Factors and places (within and outside the building): internal Blows (works), drilling, motors, wind, traffic noise, etc. Indeed there are very rare moments, in which the building no vibrates at all.

Fig. 10 shows a typical LPD spectrum (Building spontaneous vibration), where one can clearly observe two characteristic spectra:

- A small spectral range (quasi continuum) ranging from 0 to 50 Hz, high noisily. This corresponds essentially to wind induced building movement.

- The occurrence of defined peaks: 28.6 Hz, 127.8 Hz and 299.9 Hz peaks correspond to resonances of the building. In particular the frequency of 127.8 Hz is manifested every time there is a rap within the building (hammer blow). The 60 Hz peak is a noise signal arising from the electronic system

Evaluation of induced vibrations

The induced evaluations are produced, by applying selectively sound waves at some positions of the building. In all cases described below, the excitation was carried out at a mayor column located at the main laboratory and whose extension reaches the roof line with the position sensor LPD (See Fig. 3, red pointer).

LPD Measurements are not instantaneous, since, by equipment limitations, evaluations must be done point by point and for certain spectral ranges, this means about 4 hours of continuous measurements for one spectrum. Before we select an evaluation range, we make an overall scanning, searching for sensitive spectral zones

LPD1

Fig. 11 shows a first LPD evaluation, taken at the range 20 to 30 Hz. Here we obtain a remarkable resonance at 26.6 Hz., nevertheless, this peak is not constant. By other evaluations the peak at 28 Hz. result the most pronounced.

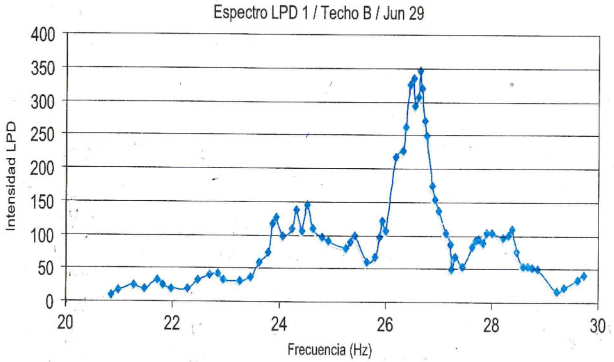

Fig. 11 *LPD1 spectrum of the induced vibration generated in the 4th floor (R Building) (range: 20 to 30 hz), it shows a predominant resonance at 26.6 Hz.*

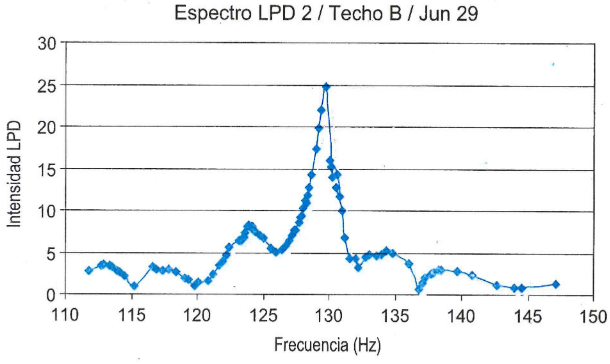

Fig. 12 *LPD2 spectrum of the vibration generated in the 4th floor (R Building) (range: 110 to 150 hz), this shows a predominant resonance at 130 Hz.*

LPD2

A second sensible range is found in between: 110 Hz to 150 Hz. Fig. 12 shows the resulting LPD evaluation. a predominant resonance ranges around 130 Hz.

LPD3

A third sensible zone is found around 300 Hz. Fig 13 shows the resulting LPD spectrum. A pronounced resonance peak is found around 298 Hz.

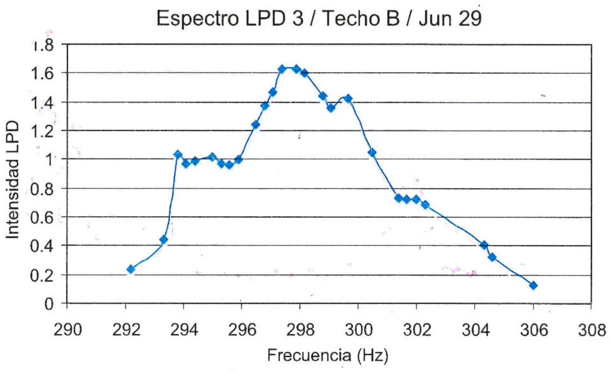

Fig. 13 *LPD3 spectrum of the vibration generated in the 4th floor (R Building) by applying sound vibrations to a mayor column in the first floor (range: 292 to 306 Hz), this shows a predominant resonance at 298 Hz.*

It is very remarkable that all sensible spectral zones (found per sound stimulation: LPD1, LPD2, LPD3) coincide very well with the maxima of the spontaneous vibrations (Fig. 10). Nevertheless, the LPD Resonance peaks are broader than the corresponding spontaneous resonance lines, which may be due to the excitation procedure (expanded sound waves). These experimental details must be cleared on a nextpProject.

The LPD stimulated measurements confirms to a great degree the results of the spontaneous evaluations (Fig. 10).

Building vibration by seismic waves

On October 6, 2008 at 19 h 51 m, an earthquake occurred in Lima (Grade 3 / IGP), which shook the building. Fig. 14 presents the LPD record of the vibration experienced by the building at that time (nearly 90 sec.).

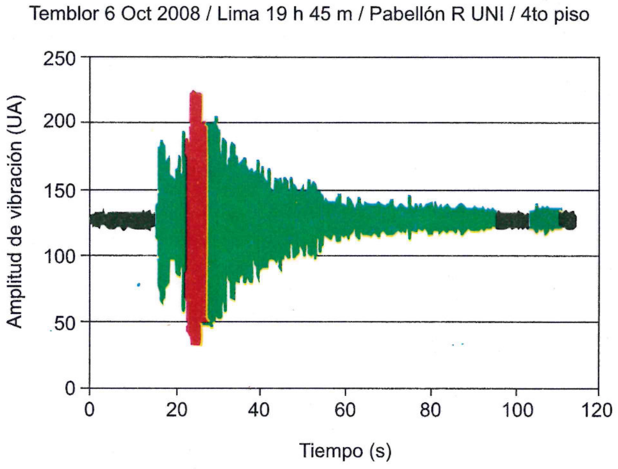

Fig. 14 *LPD spectrum of the vibration generated in the 4th floor (Structure B) during the earthquake of 6 October 2008 / 19 h 51 m.*

The vibration pattern of figure 14 shows a first trace (grey), where no significant Building oscillation is noticed.

After nearly 15 seconds it takes place a suddenly oscillation (green trace), that saturates around 22 seconds (red trace), the saturation means that the deviation at the upper floor exceeds ± 2 mm. After which, the oscillation decreases asymptotically.

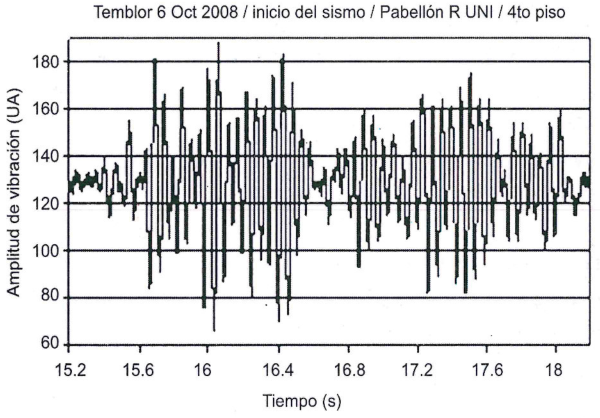

Fig. 15 *LPD fine spectrum of the vibration generated in the 4th floor (Structure B) during the earthquake of 6 October 2008 / 19 h 51 m.*

Fig.15 shows an amplification of the Period in between 15 to 18 sec. Here one can clear distinguish and estimate two main oscillatory components: the fine one of nearly 20 Hz and a coarse modulation of 0.4 Hz period approximately.

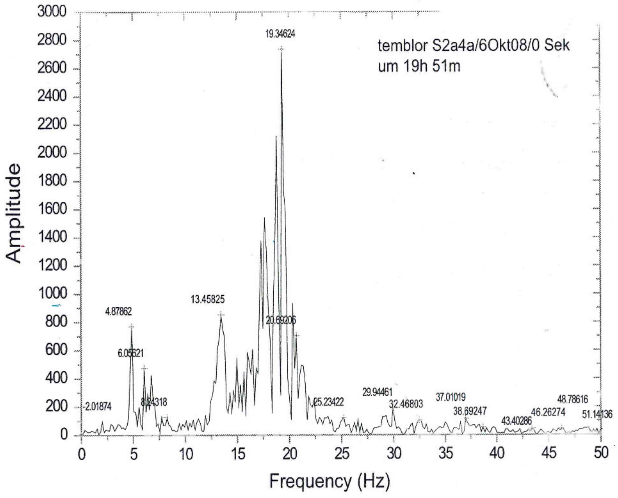

Fig. 16 *Spectral Analysis (FFT) of the LPD signal from wave pack shown in figure 15, at the beginning of the earthquake of October 6, 2008.*

A spectral analysis (FFT) of the LPD signal from wave pack (Building vibration) shown in figure 15 is performed and the result is presented in figure 16. The spectral decomposition gives a great contribution (peak) at 19.3 Hz as already estimated for the fine component. The coarse modulation (nearly 0.4 Hz) is not observed in the deconvolution process (due to the limited modulations number).

The results obtained here must be deeper analyzed in future tasks in order to clarify the peculiarities of the founded Resonance peaks and the corresponding vibration Modal physics.

CONCLUSIONS

The experimental tasks developed in this project confirm the great potential of the optical detection of structural vibrations, highlighting both the LPD evaluations of spontaneous and induced vibrations.

The present work is the first of this type to be realized in the country and even further evaluations are required to acquire experience in order to be able of diagnosing the state of buildings, the ultimate goal to be achieved.

REFERENCES

1. **Wen-Hae, L.**, "Free vibration analysis for tube-in-tube tall buildings", Journal of Sound and Vibration 303, pp. 287–304, (2007)
2. **Arnsta, M., Clouteau, D., Chebli, H., Othman, R., Degrande, G.,** "A non-parametric probabilistic model for ground-borne vibrations in buildings", Probabilistic Engineering Mechanics 21, pp.18–34, (2006)
3. **Xia_, H., Zhang, N.,. Cao, Y. M.,** "Experimental study of train-induced vibrations of environments and buildings", Journal of Sound and Vibration 280, pp. 1017–1029, (2005)
4. **De Sortis, E., Antonacci, F., Vestroni.,** "Dynamic identification of a masonry building using forced vibration tests", Engineering Structures 27, pp. 155-165, (2005)
5. **Li, Q. S., Zhang, Y. H., Wu, J. R., Lin, J. H.** "Seismic random vibration analysis of tall buildings", Engineering Structures 26, pp. 1767-1778, (2004)
6. **Tarjan, G., P. Collar, L.,** "Approximate analysis of building structures with identical stories subjected to earthquakes", International Journal of Solids and Structures 41, pp. 1411-1433, (2004).
7. **Ventura, C. E., Liam Finn, W. D., Lord, J. F., Fujita, N.**, "Dynamic characteristics of a base isolated building from ambient vibration measurements and low level earthquake shaking", Soil Dynamics and Earthquake Engineering 23, pp. 313-322, (2003)
8. **Tamura, Y., Matsui, M., Pagnini, L. C., Ishibashi, R., Yoshida, A.**, "Measurement of wind-induced response of buildings using RTK-GPS", Journal of Wind Engineering and Industrial Aerodynamics 90, pp.1783-1793, (2002).
9. **Lu, Y., Hao, H., Ma, G., Zhou, Y.** "Local-Mode Resonance and its structural effects under horizontal ground shock excitations", Journal of Sound and vibration 254(1), pp. 51-68, (2002)
10. **Zalka, K. A.**, "A simplified method for calculation of the natural frequencies of Wall-frame buildings", Engineering Structures 23 (2001) pp. 1544-1555
11. **Valera, A., Ortiz A**, "Evaluación de vibraciones en estructuras usando un Método Óptico no convencional", TECNIA, Vol. 17 N° 2, pp. 47-54, dic. 2007, Lima Perú.
12. **Ortiz, A.**, "Estudio de vibraciones estructurales por métodos ópticos", Tesis de Licenciatura, Fac. de Ciencias UNI. Nov. 2008, Lima Perú.

Correspondencia: avalera@uni.edu.pe

Recepción de originales: Abril 2008
Aceptación de originales: Junio 2008