ON THE FULL SCALE DYNAMIC BEHAVIOUR OF RC-BUILDINGS USING COHERENT LASER RADAR VIBROMETER

Véronique JOLIVET[1], Philippe GUEGUEN[2], Clotaire MICHEL[3] and Anne-Sophie SCHVEITZER[1]

[1] *Dept. Optique Théorique et Appliquée , ONERA, The French Aerospace Lab, Palaiseau, France*
[2] *LGIT, University of Grenoble, CNRS, LCPC, Grenoble, France*
[3] *IMAC, EPFL, Lausanne, Switzerland*
Email: veronique,jolivet@onera,fr

ABSTRACT :

For a long time, defining the dynamics parameters of buildings is known as a challenge for the earthquake engineering community. Even if the dynamic parameters provided by ambient vibrations (AV) cannot be fully associated to the seismic response of buildings due to the scaling effect between weak and strong motion of structures, AV based methods have since gained more and more interest because of their low cost and fast operability. One crucial parameter is the value of the fundamental frequency which can be helpful for building health monitoring, damage assessment and modelling of the buildings. Most of AV surveys consist in installing accelerometers or velocimeters in the target building and recording ambient vibrations using digital and handheld acquisition system. It can also be worthwhile and safe to have the possibility to get the resonance frequency of buildings using remote system: worthwhile because of the repeatability of the measurements without entering in buildings, and safe in case of post-earthquake assessment of the building integrity when aftershocks are able to collapse the damage buildings. This paper demonstrates the ability of coherent LIDAR, a remote LASER system, to obtain the resonance frequency of the buildings. After a brief description of the target building, the two experimental approaches based on AV and LASER techniques are presented. Finally, a cross validation of AV and LASER methods is performed.

KEYWORDS: ambient vibrations, coherent LIDAR, vibrometry, fiber LASER, structural engineering, earthquake engineering.

1. INTRODUCTION

Ambient vibration analysis is useful to define the dynamic parameters of existing buildings, more particularly for post-earthquake assessment of building integrity. Since Carder (1936), the scientific literature dealing with the interest of AV for structural and earthquake engineering is abundant (e.g., Trifunac, 1972; Celebi, 1993; Ventura et al., 2003; Boutin et al., 2005; Michel et al., 2008). After the Boumerdes (Algeria) Earthquake of May 21, 2003, Dunand et al. (2004) assessed the building post-seismic integrity using single AV recordings on the roof of damaged buildings. They showed how the frequency shift evaluated using AV could be used to complement and improve seismic survey of damaged buildings. AV surveys usually rely on installing accelerometers or velocimeters in the target building, which may be unsafe because aftershocks are able to collapse the damaged buildings. Therefore it could be worthwhile and safe to get the resonance frequency of buildings using a remote system. The purpose of this paper is to demonstrate the ability of LASER remote sensing techniques to get the resonance frequency of buildings. We report on the experimental comparison between the frequency analysis obtained using sensitive velocimeter sensor and long range coherent LIDAR sensor. The first part of the article describes the both experimental setups and the target building. Experimental results and a cross-validation of LASER and AV methods are presented in the last part.

2. DESCRIPTION OF THE EXPERIMENT

2.1. The target building

The experiment was conducted on a RC building located close to Paris (France). It is a RC shear wall structure and is divided in two blocks, the first one (B1) having 11 stories and the second one (B2) 13 stories, as shown on figure 1. Two inner cores, consisting of RC shear walls, enclose the stair wells and lift shafts located at the two opposite sides of the B1 structure. The second structure B2 is mainly composed by stair wells and lift shafts. The foundation system consists of deep piles.

Figure 1: General view of the building and position of the LASER experimentation

Even if the two parts are separated by structural joints, coupling effects under AV between the two blocks were expected. Following the PS92 French seismic code relationships between period and height of buildings, the expected frequencies are 2.1 Hz and 1.8 Hz for B1 and B2 buildings, respectively.

2.2. LIDAR system

The LASER remote sensing system we used is a coherent LIDAR (Light Detection and Ranging). It is based on an optical interferometer, which detects the Doppler shift induced on the LASER frequency by the building vibrations. Figure 2 shows the principle of the system.

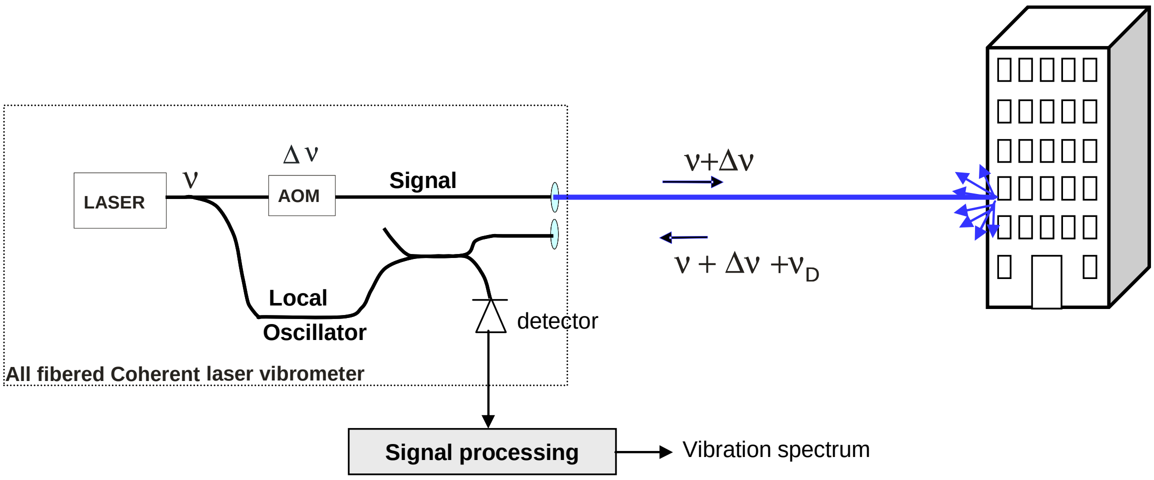

Figure 2 Principle of the coherent LIDAR vibrometer

A LASER beam at the frequency ν is split between a high power beam, called “signal” and a much lower power beam, called “local oscillator” (LO). The frequency of the signal backscattered by the target building surface suffers a Doppler frequency shift ν_D due to the surface motion, which is proportional to the difference of velocity between the LIDAR and the surface projected on the LASER line of sight. It includes the LIDAR own vibration velocity $V_{vib,LIDAR}(t)$, and the small-amplitude vibration velocity of the measured target $\mathbf{V}_{vib}$ (t) and may be expressed as:

$$\nu_{BS} = \nu + \nu_D = \nu + \frac{2}{\lambda}\,[V_{vib,rad}(t) - V_{vib,LIDAR,rad}(t)] \qquad (2.1)$$

where ν_{BS} is the frequency of the backscattered light received by the LIDAR, λ is the LASER wavelength, $V_{vib,rad}(t)$ and $V_{vib,LIDAR,rad}(t)$ are the projection of $\mathbf{V}_{vib}(t)$ and $\mathbf{V}_{vib,LIDAR}(t)$ along the LASER line of sight $\mathbf{i}_{LASER}$ (bold means vector).

The heterodyne current $i_{het}(t)$ at the output of the detector comes from the coherent mixing of the backscattered optical field with the local oscillator optical field and is phase modulated by the target surface vibration:

$$i_{het}(t) = I_0(t)\cos[2\pi.(\nu_{LO} - \nu).t + \frac{4\pi}{\lambda}.D + \frac{4\pi}{\lambda}\,a_{rad}(t) + \frac{4\pi}{\lambda}.a_{LIDAR,rad}(t) + \varphi_s(t)] + i_b(t) \qquad (2.2)$$

where I_0 (t) is the time-dependent amplitude of the current (induced by speckle), ν_{LO} is the frequency of the LO, D is the distance between the sensor and the target building surface, a_{rad} (t) and $a_{LIDAR,rad}$ (t) are the projection on the LASER line of sight of the amplitude vibrations a(t) and a_{LIDAR} (t) of the building surface and the LIDAR vibrations respectively, φs is a random phase term induced by speckle, and $i_b(t)$ is the noise current of the detection process.
In order to estimate the radial velocity of the surface vibration along time, we perform a time-frequency signal processing of the heterodyne current using a spectrogram and a centroïd measurement (Kachelmyer, 1995). Finally, the spectrum of the target surface vibration is obtained through a Fourier transform of the demodulated output.
The LIDAR built for the experiment (Fig. 3) is a bistatic all-fiber architecture, compact, easy to align with commercial components, resting on a platform for experimental convenience. The LASER wavelength is 1.5 µm with an emitted power of 1 Watt and a LO power of 500µW. Emission and reception of the LASER beam are performed with two fiber collimators (diameter 5.5mm and focal length 10 mm). As the measurement process is differential, we are both sensitive to the vibration of the target building and the own LIDAR vibration. For sake of experimental simplicity, we therefore decided to perform the measurement aiming at the ground from the inside of the building we want to measure, instead of being outside and aiming at the building (Fig. 1). The range between the LIDAR and the target is 150 m.

Figure 3 Picture of the coherent LIDAR vibrometre

Short range systems (from a few meters up to dozens) had been used yet for damage detection of bridges at close distance (Kaito et al., 2001; Kaito, et al. 2005) but a specific LIDAR has to be used when the goal is to measure vibrations in the kilometric range without retro-reflector (Cariou, 1999). The level of signal received by the detector depends, among other things, on the target reflectivity, the target distance, the telescope parameters, the LASER and local oscillator power, the turbulence and atmospheric attenuation. When we aimed at non-cooperative target at long range, a careful design to optimize the performance is necessary, because atmospheric turbulence and speckle noise arise and reduce the heterodyne current.
The Carrier to Noise Ratio measured in our experiment is 25 dB, which is sufficient to perform an efficient demodulation. We were limited to a 10 s duration of acquisition with the implemented digital acquisition system. For this reason, we computed the average of 60 windows of recordings to mitigate noise over 10 minutes.

2.3. Ambient Vibration recording system

A large number of output only modal analysis methods based on AV recordings are available in scientific literature (e;g., He and Fu, 200; Cunha and Caetano, 2005). A very simple method consists in using only the Fourier spectrum of the AV recordings getting from a single sensor placed at the building top. In this study, a CityShark acquisition system (Chatelain et al., 2000) connected to four Lennartz 3D 5s velocimeters was used for AV recordings. One sensor was kept fixed at the building B1 roof as reference for all sets of recordings and used for the normalization. We recorded 8 datasets, corresponding to 24 recording points located in the South-East stairs well of the B1 building and in the stairs well of the B2 building with one point per floor in both cases. Each sensor was oriented along the main directions of the building, i.e. in the longitudinal (L) and transverse (T) directions. AV were recorded during 15 min, sampled at 200 Hz (Fig. 2a). Each 15-minute record was divided into 50-second time windows. In each window, the signal is tapered with a cosine function (5%), the FFT computed, the spectral amplitude smoothed with Konno and Ohmachi (1998) windows (b=30), and the average of the 50-second time windows (+/- σ) computed. (Fig. 4b).

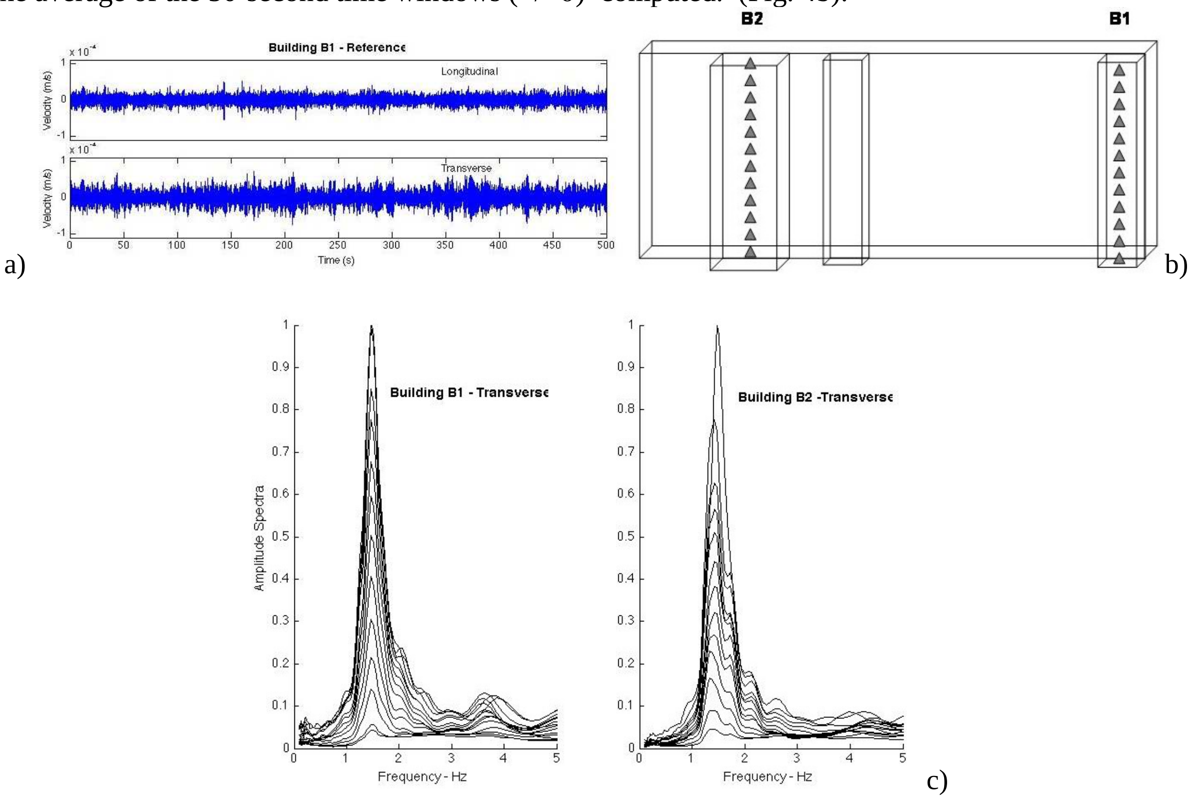

Figure 4. a) Ambient vibrations recordings in the L and T directions at the building B1 top by the reference sensor kept fixed for the experiment. b) Location of the recordings point in the B1 and B2 buidlings. c) Fast Fourier Transform spectra of AV recordings (T direction) in the B1 and B2 buildings at each floor.

The fundamental frequency of the building is 1.30 Hz in the T-direction and corresponds to the first bending mode of the building. We observe a decrease of the amplitude frequency with the floors that let us conclude on the structural relevancy of this frequency. The same frequency observed in the two buildings validates the dysfunction of the structural joint in-between B1 and B2. For the B2 building, the shape of the spectra is more complex and an additional frequency close to the first one may be at the origin of such a disturbance. A more sophisticated input only modal analysis technique could be employed for solving this hypothesis (e.g. Frequency Domain Decomposition).

3. EXPERIMENTAL RESULTS

Velocimeters installed in the building measure velocity in the three directions during 15 min, whereas LIDAR measures only the projection of the velocity along the LASER line of sight during 10s. We decided then to process the velocimeter data in the same way as for the LIDAR measurements. First, simultaneous measurements were taken with both systems in the B1 and B2 buildings. Second, we cut the 15 min long velocimeter data into 10 second long measurements and projected the L-, T-, Z- data along the LASER line of sight. Finally, the Power Spectral Density (PSD) of each data was calculated and an average on the same number of spectra as for the LIDAR measurement processing was done. Figures 5 displays the corresponding normalized LIDAR and velocimeter PSD measured in buildings B1 and B2, respectively. We can see an excellent fit between techniques of measurement, in terms of frequency value and relative amplitudes between peaks. The modal frequencies at 1.30 Hz and 1.46 Hz are detected by LASER. Moreover, Figure 5 shows that the noise level observed using LIDAR sensing is higher than for the more sensitive velocimeter sensor with a factor of about 10.

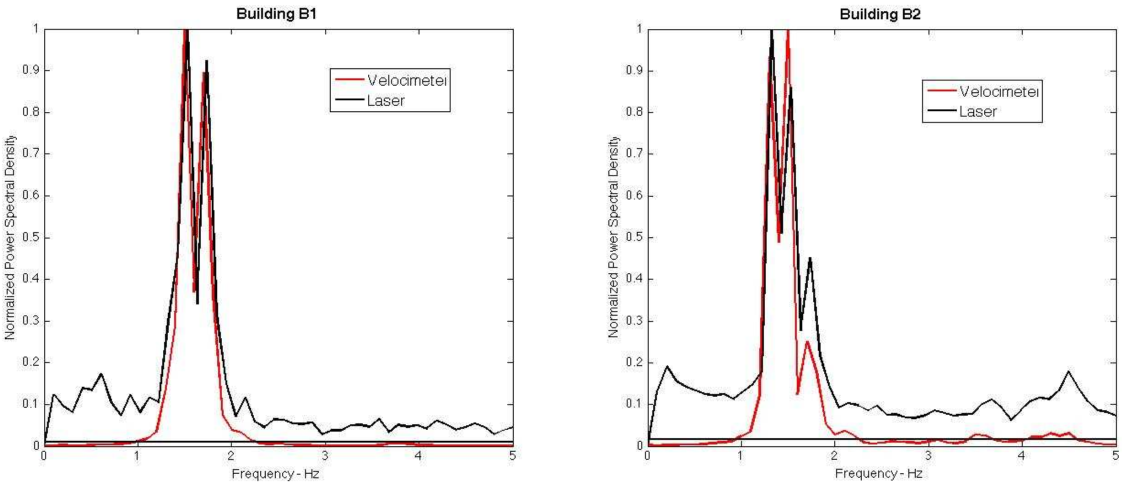

Figure 5. Comparison of the normalized power spectral density functions recorded in the experimental room of the B1 (left) and B2 (right) buildings by LASER remote sensing technique (thin line) and velocimeter sensor (thick line). 3D velocimeter recordings are projected along the LASER line of sight.

4. CONCLUSION

The ability of a LASER remote sensing type instrument for studying the frequency of existing buildings is shown in this paper. LIDAR technique has been successfully applied to a target building for frequency assessment. By comparing the frequency of vibration obtained by sensitive velocimeter sensor and coherent LIDAR sensor, we observe a good fit of the values of frequencies detected by both approaches. Even if the level of noise is higher for LASER remote sensing (10^{-6}m/s) than velocimeter (10^{-7}m/s), most of existing buildings could be checked by this method for whole urban area covering.

One of the possible applications would be to get information at distance without going into buildings that may be of great interest for post-seismic evaluation of existing building integrity. Further investigations are being planned to increase our detection capabilities for low amplitude vibrations (i.e., the lowest rise buildings) and to include a scanning process in the LASER system to measure the relative velocity at several floors for mode shape assessment.

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