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► **To cite this version:**

Philippe Guéguen, Matthieu Valla, Béatrice Augère, Didier Goular. Analysis of Reinforced Concrete Buildings Using Multipath Lidar. Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France. 2014. <hal-01021064>

HAL Id: hal-01021064

<https://hal.inria.fr/hal-01021064>

Submitted on 9 Jul 2014

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ANALYSIS OF REINFORCED CONCRETE BUILDINGS USING MULTIPATH LIDAR

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ABSTRACT

This paper compares the modal analysis of reinforced-concrete buildings obtained using sensitive velocimeters and coherent LIDAR. Ambient vibrations are recorded by these two systems and processing using operative modal analysis method for getting building frequency and mode shapes. Real-scale trials applied to five buildings located at Grenoble (France) are presented. The efficiency and reliability of the Lidar is discussed and the modal parameters measured by Lidar at a range of 200m and by in-situ velocimeters are compared. The results are in good agreement and allow us to conclude on the ability of the coherent Lidar to assess modal parameters of existing buildings at long range and without any retroreflectors placed on the structures. The results open new perspectives for remotely testing buildings, without getting inside, facilitating dynamic analysis of buildings for earthquake engineering applications.

KEYWORDS : *Lidar, modal analysis, earthquake engineering.*

1 INTRODUCTION

Since the design seismic forces in structures are frequency and damping dependent, these two parameters are the subject of particular attention in many research activities, to fix numerical [1,2,3] or analytical models [4] or to provide empirical relationships between the main characteristics (height, design, etc.) of buildings and their period of vibration found in seismic regulation documents [5,6,7,8,9]. Clinton and Heaton [10] related the evolution of the performance of building instrumentation for earthquake engineering activities since the 1960's and the beginning of the building permanent instrumentation program in US [11,12,13,14,15] and Japan [16]. With the low sensitivity of the new seismic and accelerometric sensors, ambient vibrations (AV)-based methods for modal analysis have been commonly used to monitor structures in earthquake engineering communities providing an effective tool for short- and/or long-term monitoring of structural health.

In addition, a significant amount of research has been conducted over the last two decades on non-destructive damage evaluation (NDE) based on changes in the dynamic modal responses of a structure. The basic idea is that modification of a system's stiffness, mass or energy dissipation characteristics may alter its dynamic response [17,18]. For example, a comparison of initial and final values of frequency, damping and mode shape after extreme events provides information on the post-earthquake integrity of structures [19,20,21,22]. Analysis of the damage related to variations of the fundamental frequency of the buildings is common practice in earthquake engineering since, as supported by Farrar et al. [23], frequency is probably the modal parameter that is most sensitive to change, particularly because the loss of stiffness directly impacts the frequency values [19,20,24,25,26]. Moreover, damage detection methods are also based on mode shape analysis, such as the mode flexibility method [27], the curvature flexibility method [28] and the mode shape curvature method [29].

Few applications are available in practice, in spite of the fact that the estimation of damage severity makes a significant contribution to the action of decision-makers in emergency situations

after extreme events. One of the reasons to explain this observation is that in general, the testing is performed by putting sensors in the structures, a delicate and dangerous activity in the event of seismic crises because of repeated aftershocks and of large number of buildings to be tested. The main objective of this paper is to test a remote assessment of modal parameters (frequencies and mode shapes) of existing buildings, having as objective the health monitoring. After presenting the multipath Lidar instrument used here, and the building tested, we compare the modal parameters assessment provided by Lidar and classic velocimeters deployed in the structures.

2 THE LIDAR

The system developed for this study is a triple all-fiber Lidar vibrometer [30] working at $1.55\mu\text{m}$, using polarization-maintaining fibers (Fig. 1A). In figure 1B, the backscattered wave is mixed with a portion of the signal called the local oscillator (LO). On the photodetector, the interference between the two optical waves yields a current, called the heterodyne current, whose frequency is given by the difference between the frequencies of the two optical waves. During Lidar operation, the frequency of the signal backscattered by the target building surface suffers a Doppler frequency shift which is proportional to the difference in velocity between the Lidar system and the target building surface in the direction of the Lidar line-of-sight. The frequency of the heterodyne current is thus equal to the Doppler frequency shift. These currents are then sent to the analog signal processing module, where the backscattered signals are filtered and downshifted in base band. The digitized signals are then processed in real time for in-situ spectral visualization and stored for furthermore detailed analysis.

As we are aiming at static but vibrating targets, the overall Doppler frequency shift due to target velocity is null and the carrier frequency of the heterodyne signal is centered on the frequency of the acoustic-optic modulator (AOM, Fig. 1B) frequency. In monostatic architecture, parasitic signal exists that creates crosstalk phenomena, i.e. a fraction of the power emitted by the Lidar is accidentally redirected into the reception. The parasitic signal from the back-reflection of the emitted beam on the output lens is also centered on the AOM frequency shift, preventing the frequency separation of the useful signal. All paths are bistatic (separate transmitting and receiving lenses) in order to avoid being blinded by parasitic signal due to the redirection of a fraction of power emitted by the Lidar into the reception (crosstalk phenomena).

The two first sensor heads are mounted on an automated turret (Fig. 1A), which allows a series of points to be addressed on the target building. The third sensor head is used as a time synchronization reference, sighting a fixed reference point on the target building and providing a synchronization reference for vibrations measured successively by the mobile sensor heads. The building vibration velocity is determined using the autocorrelation between one complex sample and its first neighbor. The result is accumulated over a number of complex samples. The phase of the computed autocorrelation gives the instantaneous frequency of the signal, which is proportional to vibration velocity. The output (i.e. vibration velocity) of the digital signal processing is computed every 5 ms, resulting in a vibration sampling frequency of 200 Hz. This sampling frequency is chosen in order to avoid parasitic vibrations (presence of electric motors, machine, lifts...), which appear up to 80 Hz, whereas building frequencies remain below 20 Hz. These vibrations are usually observed during experimental works conducted in structures resulting from the operating of the buildings (presence of electric motors, machines, lifts...). The reference beam, kept fixed during all the experiment, gives the time reference and the synchronization is made with the mobile beams as well as the amplitude normalization.

3 DESCRIPTION OF THE EXPERIMENT

Grenoble (France) is a dynamic city that increased in population during the late 60s. Many high-rise buildings were built at that time. In the framework of this study, five such buildings have been tested.

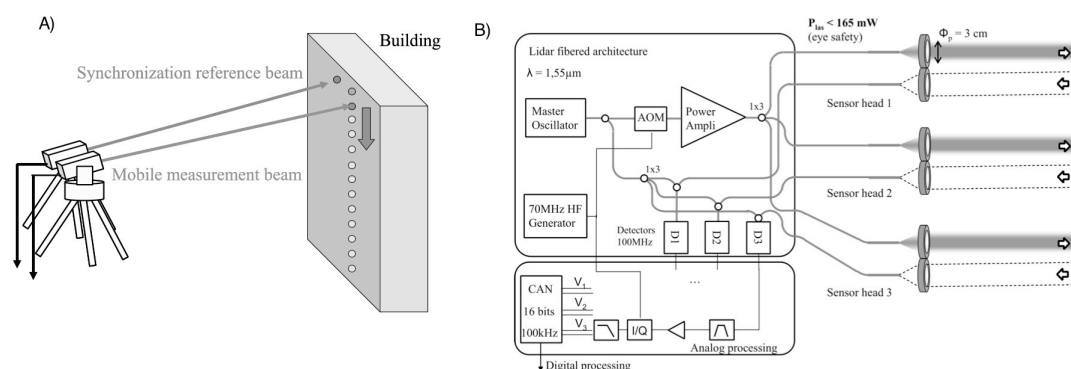


Figure 1: Description of the Lidar. A) Scheme of principle;
B) Electronical and optical description of the Lidar

The three Ile Verte towers (Mont-Blanc, Belledonne and Chartreuse) are 28-story RC-buildings. In March 2003, ambient vibrations were recorded at 15 different points in the Mont-Blanc tower (the central tower, Fig. 2) with a Cityshark II [31] and 6 velocimeters Lennartz 3D 5s. We used the Frequency Domain Decomposition method (FDD) [32] to analyse the modes of the structure. A reference site was kept at the top of the building and several sets of recordings (at 200Hz) were done moving velocimeters along the height of the building. The two first modes are 0.66, 2.69Hz and 0.85, 3.25Hz in the T and L directions, respectively [33]. For Belledonne and Chartreuse, the modal frequencies were computed using the Fast Fourier Transform (FFT) applied to the top recording done during the Lidar experiment (Fig. 3). Even if the three buildings are perfectly similar in term of design, shape and height, some variations were observed due to the presence of differences in design or due to the high sensitivity of frequency to changes confirmed recently by Mikael et al. [33]. Furthermore, a torsion mode [33] was also observed at 0.99Hz.



Figure 2 Description of the Buildings (left: Arpej buildings; right: Ile Verte towers)

We followed the same process in December 2002 in one of the two ARPEJ towers, 15-story RC-buildings in the campus. For ten years, ARPEJ2 has been used as a test bed for training activities and instrument tests. Mode shapes and modal frequencies were obtained for this building [34]. The two first modes were found at 1.17, 4.57 Hz and 1.32, 5.03 Hz in the T and L directions, respectively (Fig. 3). A torsion mode, corresponding to 1.37 Hz, was also detected on the Fourier spectra. The stability of the modes shapes over ten years allows us to assume a very stable and robust method for extracting the dynamic characteristics of existing buildings.

The Lidar experiment has followed the same process as for AV recording. One sight was kept at the top of the building as the reference and the other two sights were moved down from floor to the

bottom of the building. The Lidar was positioned on a support resting on the ground, located to allow direct sight of the full height of the building. The distance of sight for the ARPEJ buildings was around 100 m and for the Ile Verte buildings the distance was close to 300 m. After signal processing of the raw Lidar data, each file corresponded to 10 minutes of recordings with a sampling rate of 200 Hz. Gueguen et al. [35] have confirmed the Lidar records the frequencies of the target and of the support. For that reason, the Lidar support was designed to be stiff enough with respect to the classic range of building frequencies to avoid interferences. After data conversion, FDD was applied and the modal analysis was performed. The major advantage of the Lidar designed for this experiment is the have a perfect synchronization of recordings without requiring a specific reflector placed on the surface of the structure. Nevertheless, the longer sight distances introduce more noise, reducing the signal-to-noise ratio due to beam divergence of the optical wave and affecting the performance of the Lidar system. This could be resolved by increasing the performance of the Lidar but it introduces constraints on complying with the restrictive eye safety regulation.

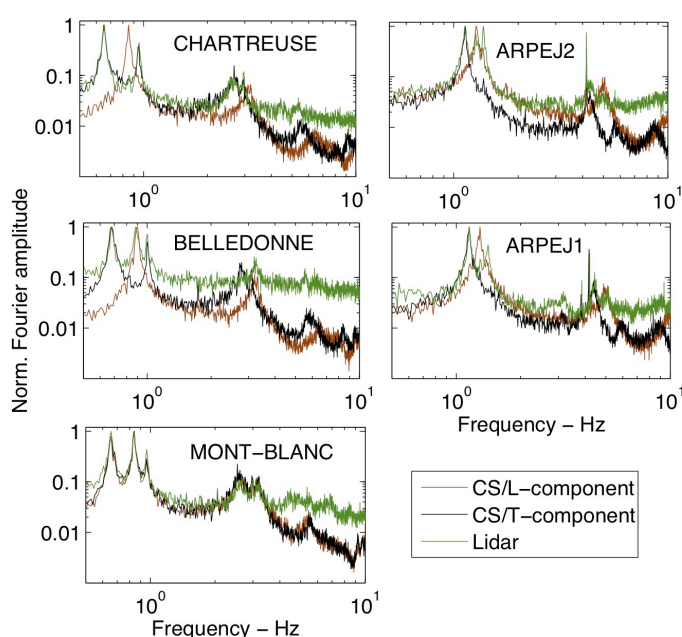


Figure 3 Fourier transforms of ambient vibrations recorded at the buildings top (left: Ile Verte; right: ARPEJ) with velocimeters (CS) and Lidar.

4 RESULTS

Fast Fourier Transform is computed at the top of the building using velocimeters and Lidar systems (Fig. 3). The Lidar detects the modal frequencies of the buildings, including longitudinal and transverse direction but also the torsion mode. Below 2 Hz, i.e. close to the fundamental frequencies of the tested buildings, the signal-to-noise ratios (SNR) are comparable, because the building vibration is large enough to be detected. At high frequency, we observed that the noise level of the Lidar is higher than that of the velocimeter, as already suggested by Gueguen et al. [35]. This low SNR introduces some drawbacks for the clear analysis of the second frequencies, visible in the 2-5 Hz range. For the Ile Verte towers, the SNR at high frequency is worse than for the ARPEJ buildings, due to the distance of sight between the Lidar and the building.

Moreover, the Lidar measures velocity along a single direction of sight. By consequence, the frequencies detected are directly influenced by the azimuth of the sight with respect to the main direction of vibration of the buildings. This is clearer for the Ile Verte buildings for which the

differences in azimuth of the sight for the three buildings tested were greater, i.e. 11° , 45° and 70° for the Chartreuse, Montblanc and Belledonne towers, respectively. For Chartreuse, the sight was close to the perpendicular axis of the building and we detected only the T direction of vibration and the torsion mode (Fig. 3). For the Belledonne tower, all three modes were recorded, with amplitude variations compared to the velocimeter results. For Montblanc, corresponding to 45° of sight azimuth, the three modes were perfectly recorded by the Lidar. This is the main drawback of the Lidar measurement technique: recording the vibration along a single direction of sight means that the modal analysis can be biased. Nevertheless, in the case of remote monitoring, we observed that the frequency values are reliable and representative of the dynamic response state of the buildings let us assume the efficiency of the Lidar for detecting the frequency variations related to changes or damages.

The singular value decompositions of the velocimeter and Lidar data for the ARPEJ2 and Montblanc towers are displayed figure 4. The same singular value decomposition is observed for both buildings whatever the equipment used. Due to the SNR, the two horizontal modes in the T and L direction are well detected, as well as the torsion mode clearly observed here. This detection is not dependent on the single sight of the Lidar along one direction. It is particularly interesting to point out the presence of parasite frequencies at 4 and 10Hz for the ARPEJ2 building, seen with both systems and certainly produced by a permanent internal source of vibration (e.g., lift or air conditioning). In both cases, 15 Hz is observed on the LIDAR, corresponding to the vibration of the Lidar support, as also reported by Gueguen et al. [35]. At high frequency, for the higher modes, the Lidar system is noisier, resulting in low resolution of the second singular value. This is clearer for the Montblanc tower, due to the increase in noise with the distance of sight (280 m for Montblanc and 120 m for ARPEJ2). In this case, the 3 Hz second mode cannot be analysed.

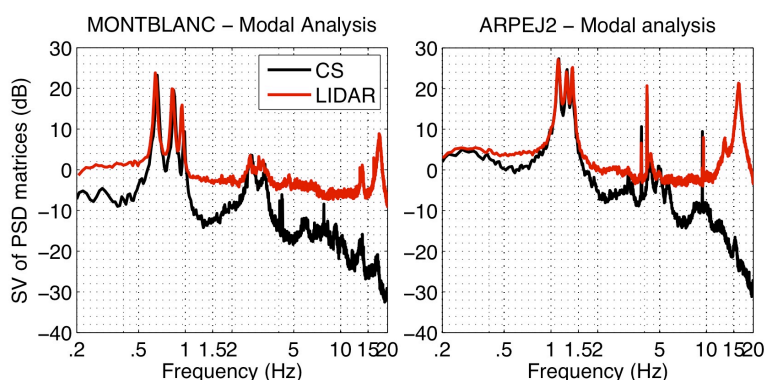


Figure 4 Singular value decomposition of ambient vibrations recorded by Lidar and velocimeter (CS) for the MontBlanc (left) and the ARPEJ2 (right) towers.

Since the singular values (frequencies) and singular vectors (mode shapes) were detected, it is possible to draw the 3D shapes of the modes, by associating with each sensor the 3D deformation of the building. This is displayed Fig. 5 for the Montblanc and ARPEJ2 buildings. In order to improve shape visualisation, we considered each floor to be stiff and undeformable, that corresponds to associate at each point of the floor the motion recorded by the sensor or the Lidar. According to the velocimeter, the Montblanc mode shapes are clearly related to bending modes in the L direction, corresponding to frequencies 0.85Hz. Because of the 3C of ambient vibrations recorded with the velocimeters, the full motion of the building can be reconstructed by modal analysis. For the Lidar, only one direction of sight is available. We therefore observe (Fig. 5) the coupling of the mode shapes of the two horizontal directions of the structure, as well as the vertical direction. The angle of deflection is related to the azimuth of the sight with respect to the building. This means that mode shape reconstruction is not possible unless we record vibrations in the direction of the perpendicular modes, even if the singular values and vectors are detected perfectly by the Frequency Domain

Decomposition. Moreover, the Lidar sights from the ground level and the vertical motion are also present in the coupling mode shapes defined by FDD. Nevertheless, this drawback does not reduce the major advantage of the Lidar equipment, i.e. performing remotely dynamic characteristic assessments of existing buildings, from one site without entering the building and considerably reducing the time (and therefore cost) of the experiments. For information, we assessed the three Ile Verte towers in 6 hours, which is approximately the same as the time required using the velocimeter.

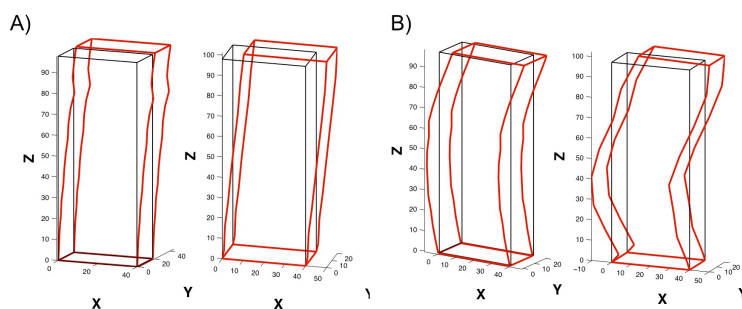


Figure 5 Shapes of the first (A) and second (B) mode using velocimeter (left) and Lidar (right) systems for the Mont-Blanc Tower

5 CONCLUSIONS

The large-scale instrumentation and monitoring of existing buildings is of more than academic interest. Testing buildings provides information on safety by evaluating the variation of their elastic properties, often related to damage. In view of the number of buildings that must be tested after an extreme event, the development of remote systems, such as the Lidar, may be the key to improving the operability and efficiency of decisions. The assessment of changes between the physical properties of structures before and after earthquakes can help classify buildings as being suitable for immediate occupancy, requiring further and additional analysis or for demolition. Moreover, the long-term monitoring of buildings is also critical for decision makers and local authorities in order to check the effects of ageing and to assess the remaining life span of their structures.

In this paper, we have reported on the development and field trial of a 3-path Lidar vibrometer for this purpose. We have showed that application-related constraints are fulfilled: low velocity noise, real-time signal processing, compactness and laser safety. Autonomous and operability of the equipment was demonstrated during a vibration measurement campaign at long distance of sight. A good fit was observed between the modal frequency and mode shape values detected by Lidar and classical velocimeter. Despite a higher level of noise for the Lidar than for the velocimeter, most of the existing buildings could be monitored using this remote sensing method for large urban areas. The drawback related to the single direction of sight can be compensated by the efficiency of remote assessment of frequency and mode shapes, giving a fast and accurate assessment of the structural health. Shorter experiment times and reliability of measurements lead us to imagine broad application on the scale of a city, allowing long-distance and repetitive scanning of structures.

ACKNOWLEDGMENTS

This work was supported by the French Research National Agency (ANR) under the RiskNat program (project URBASIS n°ANR-09-RISK-009).

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