Remote modal study of reinforced concrete buildings using a multiple-path Lidar vibrometer

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15 WCEE
LISBOA 2012

SUMMARY:
Coherent Lidars are able to finely measure the vibration velocity of remote targets. This allows Operative Modal Analysis (OMA) of potentially damaged buildings, for their diagnosis at a safe distance after a seismic event. As a next step from our previous work validating this method for modal frequency determination, we have assessed its capability to extract the full modal parameters of RC buildings, including mode shapes, using multiple ambient vibrations measurements by Lidar on the entire structure.
We report on the development and field trial of a 3-path Lidar vibrometer for this purpose. After a description of the system, we show that application-related constraints are fulfilled: low velocity noise, real-time signal processing, compact and laser safety. Then, we present the results of a real-scale trial on 3 buildings in Grenoble, France. We discuss the reliability of this technique for remote structural diagnosis with a comparison of modal parameters, as measured by Lidar at 200m range and in situ velocimeters.

Keywords: Lidar, Vibrometer, Modal study

1. LIDAR VIBROMETER SYSTEM OVERVIEW

1.1. Coherent Lidar principle

With a coherent Lidar, such as illustrated in Figure 1, the backscattered wave is mixed with a portion of the signal called the local oscillator. On the photodetector, the interference between the two optical waves yields a current, called heterodyne current, whose frequency is given by the difference of the frequencies of the two optical waves.

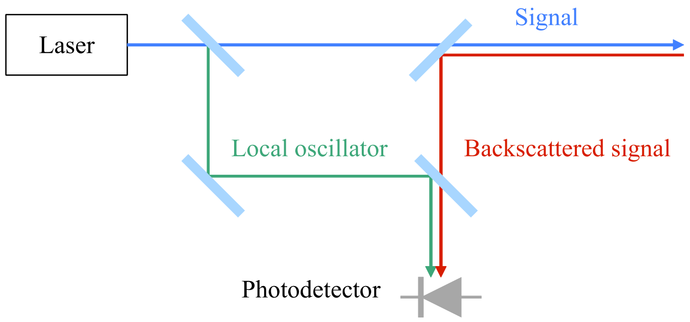

Figure 1: Coherent Lidar

During Lidar operation, the frequency of the signal backscattered by a targeted 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 building targeted surface projected on the Lidar line of sight:

$$\nu_D = \frac{2}{\lambda} V_{building/lidar}(t).I_{lidar} \tag{1.1}$$

Where λ is the Lidar wavelength, $V_{\mathrm{building/Lidar}}(t)$ is the relative velocity vector between the Lidar and the building and I_{Lidar} is the normalized Lidar line of sight vector. At this point, one should notice that the Doppler frequency shift also includes the Lidar own vibration.

The frequency of the heterodyne current is thus equal to the Doppler frequency shift. Considering vibrometry, since the Doppler frequency shift is low, it is convenient to add a constant frequency shift with a modulator. In our case we use an acousto-optic modulator.

1.2. System overview

The system developed for this study is a triple all-fiber Lidar vibrometer (Cariou and Augère, 1999) working at 1.55µm, using polarization maintaining fibers. Fiber components are low cost, reliable and allow the design of a robust and compact instrument, suitable to field tests. Figure 1 illustrates the Lidar general configuration.

A DFB fiber Laser from Koheras is used as a master oscillator: its 30 mW of output power is split between the "local oscillator" (LO) beam and the "signal" beam. The signal beam goes through a 70 MHz frequency shifter acousto-optic modulator (AOM) and is then amplified using a Keopsys fiber amplifier (Power ampli). Both LO and signal power are splits in three, in order to send signal power for the three sensor heads and LO power for the three detectors. The detectors are three InGaAs photodetectors with a 100 MHz bandwidth and a low level of noise. At detector level, the three backscattered signal coming from the building are mixed with LO power. The resulting heterodyne currents are then sent to the analog signal processing module, where the backscattered signals are filtered and downshifted in base band and digitized in phase and quadrature (I/Q) at a sampling frequency of 100 kHz using a National Instrument acquisition card. The digitalized signals are then processed in real time for in situ spectral visualization and stored for further and deeper analysis.

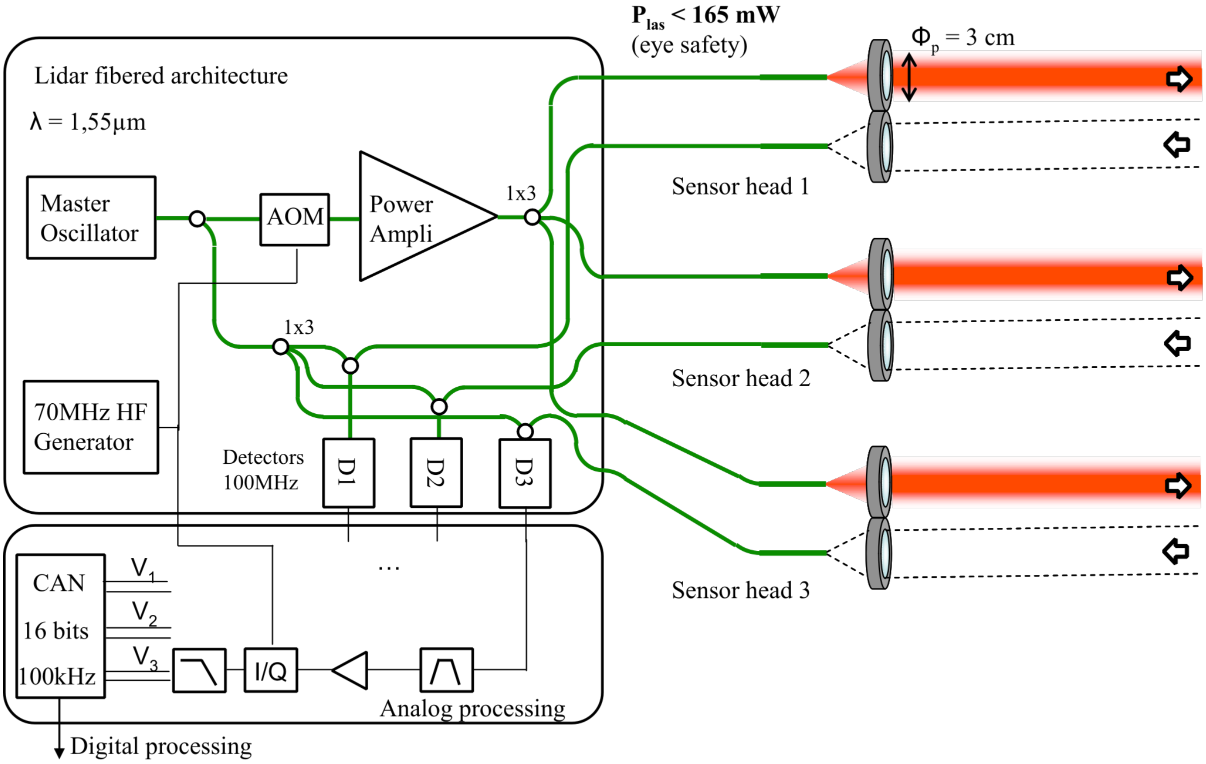

Figure 2: Lidar configuration

Each sensor head use two 3 cm diameter collimating optics which allows measurements up to a few hundreds of meters before a noticeable loss of carrier to noise ratio due to beam divergence. As we are aiming at static targets, the global Doppler frequency shift due to the target velocity is null and the carrier frequency of the heterodyne signal is centered on the AOM frequency. In monostatic architecture, the parasitic signal that comes from the back reflection of the emitted beam on the output optic would also be centered on the AOM frequency shift. To avoid this, all paths are bistatic (separate transmitting and receiving optics) in order to avoid being blinded by this parasitic signal.

The two first sensor heads are intended to be moveable and are mounted on an automated turret, which allows addressing successively several points of the targeted building. The third sensor head is used as a time synchronization reference. It aims at a fixed reference point of the targeted building, providing a synchronization reference for vibrations measured successively by the mobile sensor heads.
During the trials described hereafter, the system was operated at low output power (150 mW on each sensor heads) to comply with extensive eye safety regulations when buildings were being scanned.

In terms of digital signal processing, the building vibration speed is determined using an autocorrelation first lag (AFL) estimator. The autocorrelation between one complex sample and its first neighbor (first lag) is computed. The result is accumulated over a number of complex samples. The phase of the computed autocorrelation yields the instantaneous frequency of the signal, which is proportional to the 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 to cope with parasitic vibrations which appear up to 80 Hz, whereas building vibrations stay below 20 Hz.

1.3. Vibration map reconstruction

The multiple-beams configuration allows synchronizing several successive measurements performed on the building surface to determine its vibration spectrum along several points. Without a common time reference, all the relative phase information between the spectra measured at various points is lost. As shown in Figure 2, the time reference is given by the synchronization reference beam, measuring the vibration of the same point at each new measurement by the mobile beam.

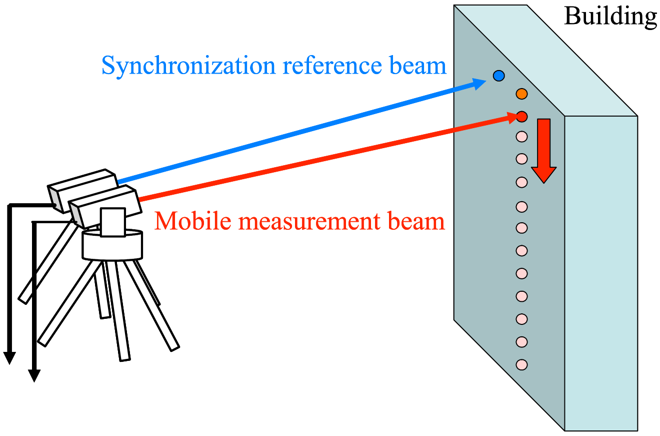

Figure 3: Multiple measurement beams configuration

The data processing used to retrieve the phase-referenced vibration spectrum at each point is also described in Figure 3. We stress that spectral accumulation on the same point (in order to average out measurement noise and affine modal peaks on the spectrum) is to be done as a last step. The spectral data can be linearly interpolated between measurement points to construct a map of the amplitude and phase of the vibration velocity on the surface of the building at each frequency.

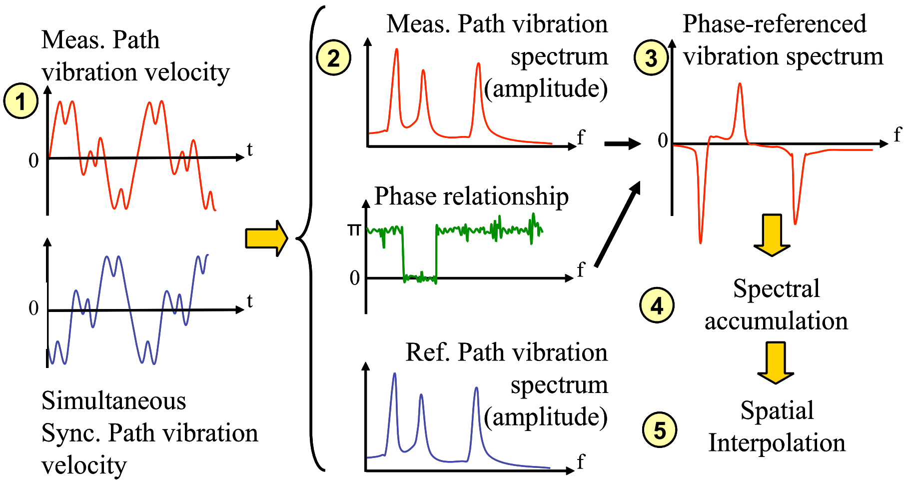

Figure 4: Multiple measurement beams data processing

This well-known technique, also used in (Halkon et al., 2004), allows the study of surface vibrations on a whole target with a simple, low-power and low-cost system with two beams and two photodiodes, as opposed to an imaging system with a matrix detector.

2. FIELD EXPERIMENT

2.1. Building description

We performed several tests in Grenoble (France) comparing the dynamic characteristics of five buildings (Figure 5) obtained with Lidar technique and classical experiments consisting in recording ambient vibrations at each floor with velocimeters.

Figure 5: Description of the five buildings (ARPEJ1 and ARPEJ2, upper row - Ile Verte towers, lower row) tested by ambient vibrations and Lidar techniques. The red triangle corresponds to the position of the Lidar for recordings and the orientation of the buildings are provided by the black narrows.

Ile Verte towers are three identical buildings: Montblanc, Belledonne and Chartreuse. These towers are 30-storey RC buildings built between 1963 and 1967. During this period, they were the tallest buildings in Europe (H =105m). The structure is a rhombus of 40×20m, the structural strength system is made of two main RC shear walls, continuous throughout their height, completed by small RC walls in the two horizontal directions. Lateral resistance is mainly supported by shear walls, providing two disconnected systems for lateral resistance.

Arpej towers 1 and 2 are twin 16-storey RC buildings (L×T×H=28×12×56m) built in the 1970s on the Grenoble University campus. The story height is regular between the 2nd and 16th floors (3.3m) and larger on the first floor (5.5m). Its structure is based on an RC frame with two RC shear walls at the ends in the transverse direction and an RC shear wall core for lift shafts and stairwells.
More information concerning these buildings can be found in Michel et al. (2012).

2.2. Ambient vibration experiments and Lidar measurements

In each building, a temporary experiment was performed to determine the modal frequency. Ambient vibrations were recorded using a CityShark 24-bit acquisition system (Chatelain et al., 2000) connected to one Lennartz 3D 5s seismometers, having a flat response between 0.2 and 50 Hz. 15 min of data were recorded at a frequency rate of 200 Hz in each building, on the top floor.

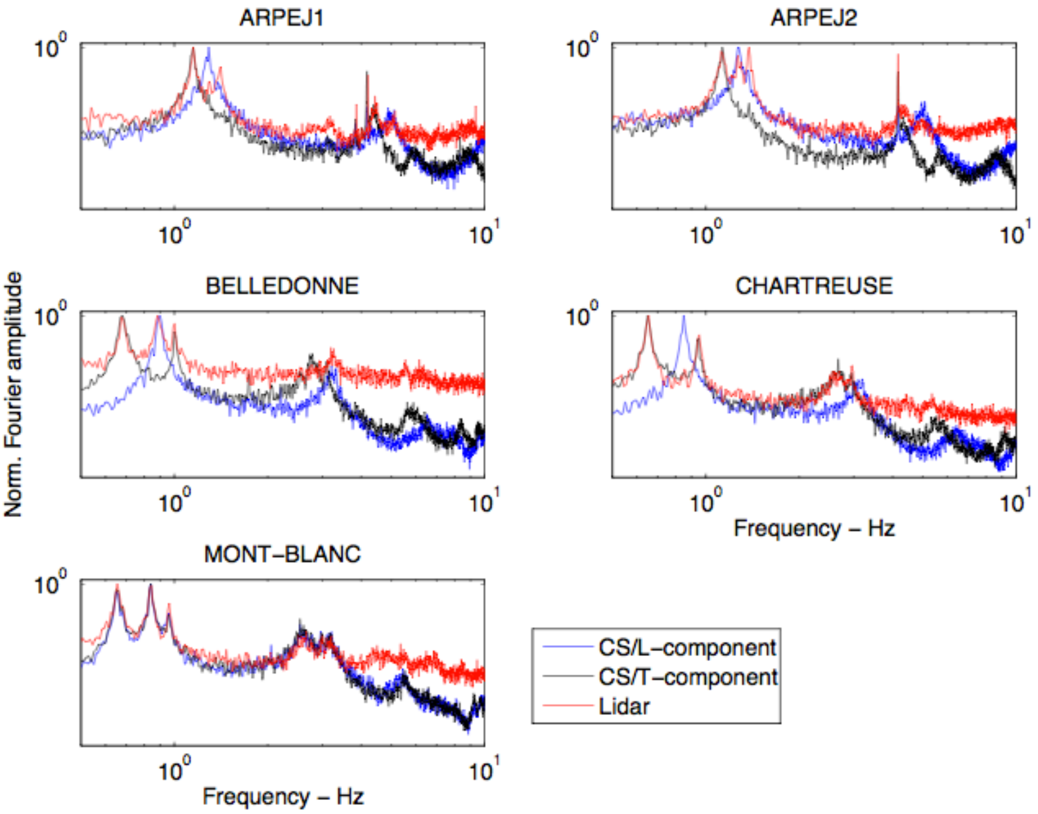

Figure 6: Fourier transform of the ambient vibrations recorded in the L (blue line) and T (black line) direction of the building and of Lidar recordings (red curve) at the top of the building.

For the ARPEJ1 building (Figure 6), the longitudinal and transverse modes correspond to 1.15 and 1.29 Hz, respectively. The same value of frequencies are also observed with Lidar technique, the differences being at high frequency, the Lidar being less sensitive than velocimeter as shown by Gueguen et al. (2010). We observe also that the torsion mode is also observed at 1.41 Hz, the azimuth between the Lidar position and the orientation of the building providing more information in the Longitudinal than transverse direction. For ARPEJ 2 building, similar observations are reported, with longitudinal, transverse and torsion modes corresponding to 1.12, 1.28 and 1.38 Hz, also observed with Lidar. In this case, the azimuth of the building with respect to the Lidar position provides the same information in the three directions.

This is also the case for the Ile verte Towers, for which the azimuth are different for the three buildings. For Belledonne, the three frequencies (0.68, 0.86 and 1.01 Hz for the T, L and torsion modes) are also detected with the Lidar while for the Chartreuse and Mont-Blanc towers, the three modes are more or less detected by Lidar, depending on the azimuth of the Lidar. For example, for the Chartreuse tower, Lidar recorded only in the T direction and thus no information is available for the L mode.

Nevertheless, for the 5 buildings, Lidar and Ambient vibrations provide the same assessment of frequencies, and the differences are provided at high frequencies (higher modes) where the sensitivity of the Lidar did not provide relevant information.

2.3. Modal analysis at the ARPEJ 2 tower

For ARPEJ 2 building, an extensive experiment was also performed to determine the modal model. Ambient vibrations were recorded on each floor with a Cityshark II (18 synchronized channels) 24-bit acquisition system connected to 6 Lennartz 3D 5 s seismometers, having a flat response between 0.2 and 50 Hz. Several 15min data sets were recorded at a frequency rate of 200Hz, with one reference sensor on the top floor. This provides a reference point to normalize and combine all the components of the modal shape (Michel et al., 2010). We used the Frequency Domain Decomposition technique (Brincker et al., 2001) to evaluate the modal parameters of the structures (frequencies, damping and mode shapes).

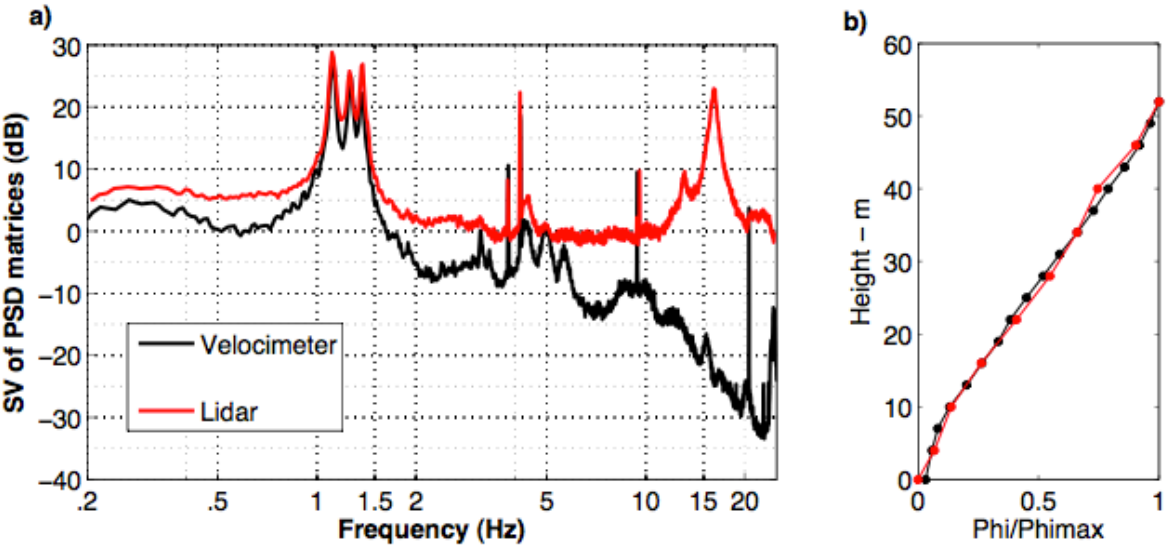

Figure 7: singular value decomposition using the FDD method (a) and correspond mode shape for the first bending mode (b) computed at the ARPEJ 2 building. Symbols on (b) correspond to the location of recordings by Lidar or velocimeters.

The Singular value spectra for Lidar and velocimeter recordings are displayed in Figure 7a. We observe that the two techniques provide the same spectra, providing information on the three first modes (L, T and torsion modes). Moreover, we also observe that we have the same shape of the spectra at high frequency, until 10 Hz, confirming the building origin of the peak value at 10 Hz. The shape of the first longitudinal bending mode is given Figure 3b, with the two techniques. We also observe a good fit between both techniques. Further studies and analysis will be performed for comparing the results for the other buildings and the influence of the azimuth for modal analysis.

3. CONCLUSION

We have reported on the development and field trial of a 3-path Lidar vibrometer for the remote study of modal parameters of buildings. Autonomous operation has been demonstrated during a vibration measurement campaign over five buildings in the French city of Grenoble.

By comparing the vibration data obtained by sensitive velocimeter sensors and coherent Lidar vibrometer sensor, we observe a good fit of the values of modal frequencies and of mode shape detected by both approaches.

Even if the level of noise is higher for Lidar (10^{-6} m/s) than velocimeter (10^{-7} m/s), most of the existing buildings could be checked by this remote sensing method for whole urban area covering.

AKNOWLEDGEMENT

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

REFERENCES

Cariou, J-P and Augère, B. (1999). Performance of an erbium Laser vibration sensor. *SPIE Coherent LASER Radar: Technology and Applications* **3707**, 491-498.

Chatelain, J.-L., Guéguen, P., Guillier, B., Frechet, J., Bondoux, F., Sarrault, J., Sulpice, P. and Neuville, J. (2000). Cityshark: a user-friendly instrument dedicated to ambient noise (microtremor) recording for site and building response studies. *Seismological Research Letters* **71:6**, 698–703.

Halkon, B.J. and Rothberg, S.J. (2004). Synchronised-scanning laser vibrometry. *Proceeding of sixth international Conference on vibration measurements laser tech* **5503**, 260-271.

Michel, C., Guéguen, P. and Causse, M. (2012). Seismic vulnerability assessment to slight damage based on experimental modal parameters. *Earthquake Engineering and Structural Dynamics* **41:1**, 81-98.

Michel, C., Guéguen, P., El Arem, S., Mazars, J. and Kotronis, P. (2010). Full Scale Dynamic response of a RC building under weak seismic motions using earthquake recordings, ambient vibrations and modelling. *Earthq. Engng and Struct. Dyn*. **39**, 419–441.

Guéguen, P., Jolivet, V., Michel, C. and Schveitzer, A.-S. (2010). Comparison of velocimeter and coherent Lidar measurements for building frequency assessment. *Bulletin of Earthquake Engineering* **8:2**, 327-338.

Brincker, R., Zhang, L. and Andersen, P. (2001). Modal identification of output only systems using frequency domain decomposition. *Smart Materials and Structures* **10**, 441–445.