

# Multiple-path LIDAR vibrometer for remote modal study of reinforced concrete buildings

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## Introduction

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 [1] validating this method for modal frequency determination, we have assessed its capability to extract the full modal parameters of reinforced concrete 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, compacity and laser safety. Then, we present the results of a real-scale trial on buildings at ONERA Palaiseau and in the city of Grenoble, France. We discuss the reliability of this technique for remote seismic integrity structural diagnosis.

## Laser radar vibrometer system overview

The system developed for this study is a triple all-fiber lidar vibrometer working at  $1.55\mu\text{m}$ , using polarization maintaining fibers. Fiber components are low cost, reliable and allow the design of a robust and compact instrument, suitable to field tests.

As shown in Figure 1, the master oscillator is a Koheras DFB polarized fiber laser delivering up to 100 mW at  $1.55\mu\text{m}$  with a linewidth as low as 3 kHz. For each one of the three paths, the chosen 30mW output is split into two beams. One is frequency shifted using a 70 MHz acousto-optic modulator (AOM) and amplified through a polarization maintaining Keopsys commercial fiber amplifier (Power amplifier) before being split in three beams emitted toward the building. The other one is kept as a reference, split in three beams sent to three fiber couplers where they are mixed with the three backscattered signal coming from the building. Detection of the heterodyne currents is done using three InGaAs photodetectors with a 100 MHz bandwidth and a low NEP ( $\text{NEP} = 8.3\text{ pW}/\sqrt{\text{Hz}}$ ). After band pass filtering, the heterodyne currents are downshifted in base band and are digitized in phase and quadrature (I/Q) at a sampling frequency of 100 kHz using a National Instrument acquisition card.

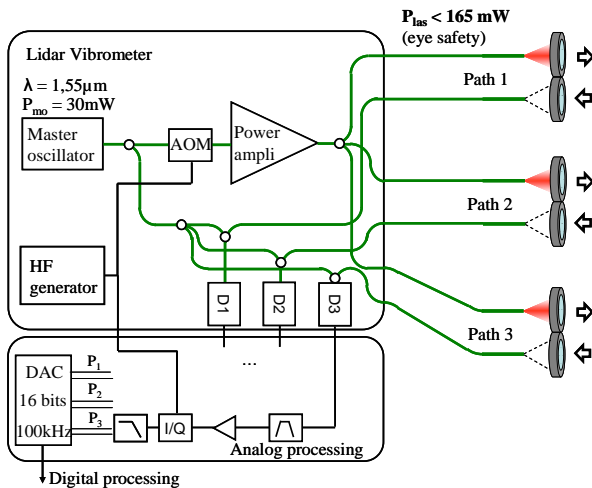


Figure 1. Path measurement configuration

The lidar vibrometer is composed of three identical paths, with parallel architectures except for the master oscillator and erbium-doped fiber amplifier that are shared. Here, we rather focus on the specificities of the three paths system.

All paths use 3cm 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 backreflection of the emitted beam on the output optic would also be centered on the AOM frequency shift. To avoid this, all paths are bistatic in order to avoid this parasitic signal.

Path 1 and 2 are intended to be measurement paths and are mounted on an automated turret, which allows addressing several points of the target successively. Path 3 is used as a synchronization path. It aims at a fixed reference point of the targeted building, providing a synchronization reference for vibrations measured successively by the mobile measurement paths.

During the trials described hereafter, the system was mostly operated with low power (150mW on each path) 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 80Hz, whereas building vibrations stay below 20Hz.

## Vibration map reconstruction

The multiple-paths 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 the left side of 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.

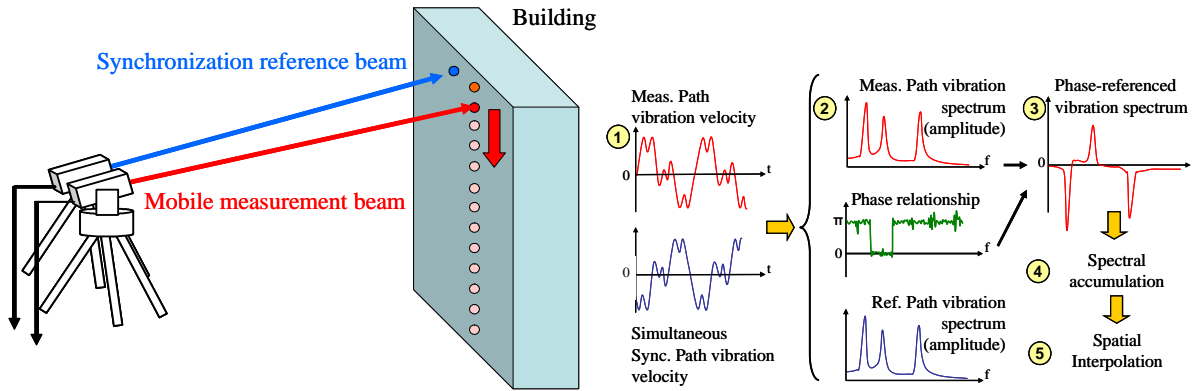


Figure 2. Path measurement configuration (left) & Multiple-path measurement processing (right)

The data processing used to retrieve the phase-referenced vibration spectrum at each point is also described in the right side of Figure 2. 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.

This well-known technique, also used in [2], 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.

## Field trial results

Field trials were conducted at ONERA center of Palaiseau in France, on the water tower shown in the left side of Figure 3. The water tower height is 26 m, and the lidar is placed on a car park at a distance of 100 m. The lidar can be operated from a car, as shown in the right side of Figure 3. Electrical power can be provided by a compact generator for full autonomous operation. The lidar sensor head should be installed with all care to ensure maximum stability.

The left side of Figure 4 shows the measurement set up on the water tower:

- Path n°1 measures vibrations on the building at different heights in order to acquire data for modal analysis.
- Path n°2, aimed on the building's bottom where we expect the least possible building motion, is used as a fixed reference. All measurements from path n°1 will be analyzed relative to measurements from path n°2.
- Path n°3, aimed on the building's top where we expect building motion, is used as the synchronization reference.



Figure 3. Lidar trial on water tower at ONERA Palaiseau (left) & Autonomous lidar operation from a car (right)

The center of Figure 4 shows the spectrum of the building vibration velocity. This spectrum is a spatially averaged spectrum because data from all six measurements points of path 1 have been used. The vibration spectrum has been scaled so that data can be read in terms of absolute vibration velocity amplitude. The averaged vibration spectrum shows that vibration velocities down to  $1 \mu\text{m.s}^{-1}$  can be measured. More information on noise in lidar vibrometry can be found in [3]. The spectrum clearly shows a strong vibration peak at 2.1 Hz which should be the signature of the water tower's fundamental mode.

The right side of Figure 4 shows the results of the modal analysis of the water tower's fundamental mode at 2.1 Hz. The motions of all measurements from beam n°1 are found to be in phase (as expected from a fundamental mode), with increasing amplitude with height. The maximum measured speed amplitude is  $7.8 \mu\text{m.s}^{-1}$ , and the corresponding maximum motion amplitude is not higher than 600 nm.

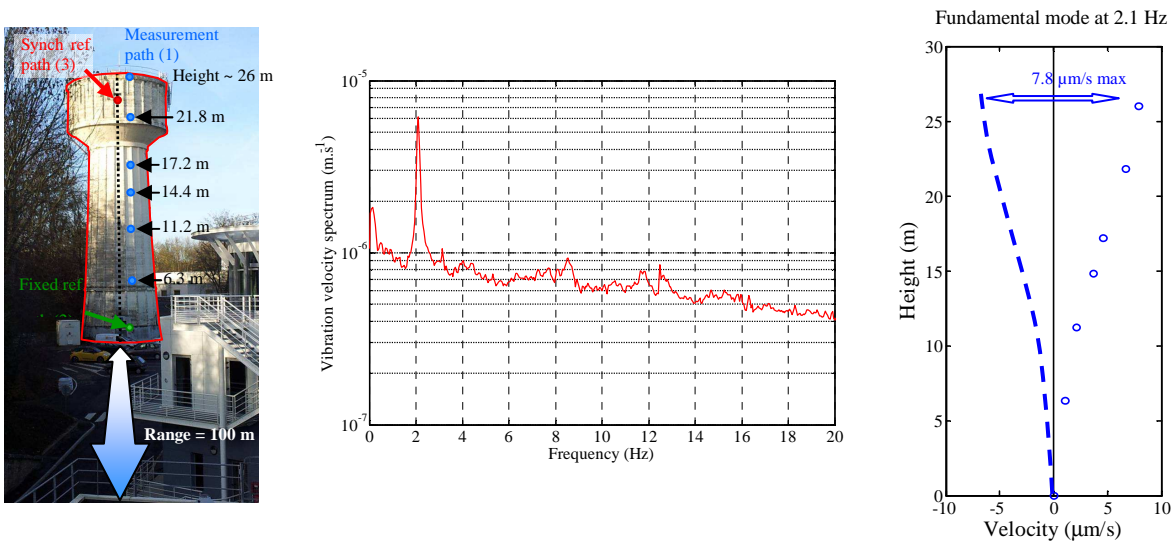


Figure 4. Modal analysis of the fundamental mode of the water tower

A matter of interest for the seismic scientific community is to measure the building's damping factor. The vibrations of buildings are mostly due to wind and natural micro seismic events which happen randomly. Those micro seismic events are brief enough to be considered as impulse. Extracting them from the recorded building vibrations allows us to estimate the building impulse response.

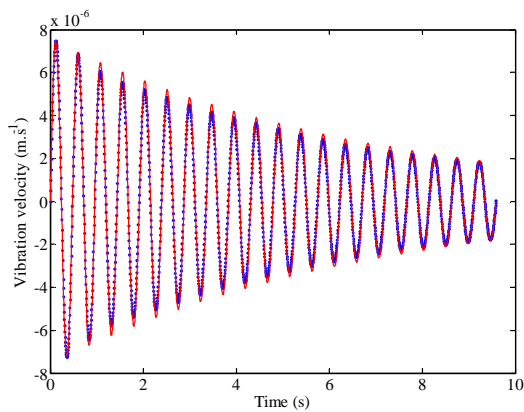


Figure 5. Water tower impulse response (blue: accumulated data, red: best fit with an exponential decay with damping factor  $\beta = 1.15\%$ , and modal frequency  $f_0 = 2.085$  Hz)

The Figure 5 shows the water tower impulse response, which has been computed using 15 minutes of vibration data. Data acquisition of 15 minutes is long enough to extract a thousand of micro seismic events, which allow a good estimate of a building impulse response. The blue dot cloud is the impulse response extracted from the lidar vibrometer data, and the red plain curve is the best model fit (exponential decay with time). Figure 5 shows a good agreement between the measurement and the modeled exponential decay.

Values of the modal frequency and damping coefficient for the water tower's fundamental mode have been computed using the random decrement vibration signature analysis technique [4]. Value of modal frequency is found to be 2.085 Hz, and value of the damping coefficient is 1.15%. According to us, the results are consistent with what could be expected from building of that type.

## 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. Our study shows that application-related constraints were all fulfilled: low velocity noise ( $1 \mu\text{m.s}^{-1}$ ), real-time signal processing, compacity and laser safety.

Autonomous operation has been demonstrated on a water tower inside ONERA Palaiseau. According to seismic specialists from ISTerre, the obtained results are consistent with what could be expected from building of that kind. At the conference talk, we will present new results from a building vibrometry campaign performed in the city of Grenoble, France. We will report on comparison between laser vibrometry and simultaneous in situ seismic sensors measurements from ISTerre.

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