

Application Note

Laser Doppler Vibrometry for Structural Health Monitoring of Civil Infrastructure

1. Introduction

Structural Health Monitoring (SHM) of large civil infrastructures such as bridges, viaducts, towers, and buildings require accurate, reliable, and often long-term measurements of structural dynamic behavior. Traditional sensing technologies, including accelerometers and strain gauges, are widely used but present limitations related to **installation complexity, low-frequency performance**, spatial coverage, and maintenance.

Laser Doppler Vibrometry (LDV) has emerged as a powerful non-contact optical measurement technique capable of addressing many of these challenges. This article presents an overview of LDV principles and its types, its applicability to civil infrastructure monitoring, its advantages and limitations in comparison with conventional SHM sensors and finally **some examples of applications in civil engineering**.

2. Principles of Laser Doppler Vibrometry

Laser Doppler Vibrometry is an interferometric technique that measures the velocity of a vibrating surface by detecting the Doppler frequency shift in reflected laser light. A coherent laser beam is directed at the target surface, and the frequency difference between the emitted and reflected light is proportional to the surface velocity along the laser line-of-sight.

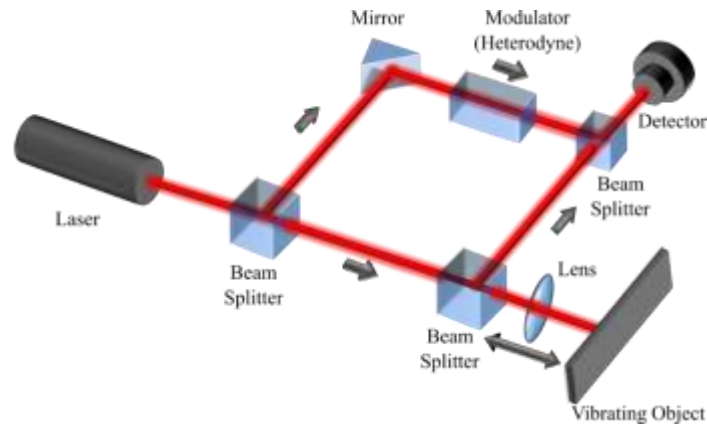


Figure 1: schematic principle of the optical setup needed to measure Laser Doppler Vibrometry

LDV systems directly provide velocity versus time, which can be integrated to obtain displacement or differentiated to obtain acceleration, and in this case the signal is directly comparable to an accelerometer.

Some LDV can measure down to real DC frequencies and therefore they can be used as **velocimeters**, which is of great usefulness in the case of deflection measurements of bridges, for example, because the deflection is slow (minutes).

3. Relevance of LDV for Structural Health Monitoring

LDV offers several key advantages that make it particularly suitable for SHM of large-scale structures:

- Rapid deployment **reducing installation time**: the use of traditional contact sensors such as accelerometers, strain gauges, inclinometers, potentiometers and optical fiber sensors requires a team of workers, elevations means, safety concerns, etc. LDV is fast to set up (minutes) and just requires one operator.
- LDV allows measurements from beneath or alongside the structure, often enabling full-span monitoring from a single installation location, which is difficult to achieve with conventional sensor networks.
- Non-contact measurement, enabling monitoring of inaccessible or operational structures or avoiding contact with heritage buildings and art pieces

- High sensitivity at low frequencies, where many civil structures exhibit their fundamental modes
- No mass loading, preserving the true dynamic characteristics of the structure
- Wide frequency bandwidth, from sub-Hz (or DC) to several kHz

These features are especially valuable for infrastructure subjected to live loads such as traffic, wind, and occupancy.



Figure 2: LDV deployment in the field is fast and easy

LDV natively measures velocity, which is a fundamental dynamic quantity for modal identification and damping estimation. Through numerical integration, LDV provides accurate displacement estimates, particularly at low frequencies where accelerometer-based approaches suffer from drift and noise amplification.

4. Applications to Bridges and Viaducts

Bridges and viaducts typically exhibit dominant vibration modes in the 0.2–10 Hz range, making them well suited to LDV-based monitoring. Typical applications are:

- Operational modal analysis under traffic loads
- Identification of natural frequencies, mode shapes, and damping ratios
- Monitoring of traffic- or train-induced vibrations
- Validation and updating of numerical (finite element) models
- Detection of stiffness changes and damage-sensitive indicators



Figure 3

5. Applications to Towers, Masts, and Tall Buildings

Tall and slender structures such as towers and high-rise buildings are often governed by wind-induced vibrations, low-frequency sway and torsional modes and show small accelerations but significant displacements. LDV is particularly effective in these scenarios due to its high displacement accuracy at low frequencies, ability to operate remotely from ground level and the minimal installation and access requirements

For example, in the **wind energy sector**, the foundations of the towers suffer from huge efforts during their lifetime. Periodic inspections are therefore required. A quick way to assess the status of the foundation is to measure the eigenfrequencies of the tower, which show a shift to lower frequencies in case of degradation of the foundations because of the lower stiffness.



Figure 4

6. Single-point fixed, single-point scanning multi-point LDV Systems

6.1 Single-Point fixed and scanning LDV

Single-point fixed LDV systems measure vibration at one location at a time and are commonly used for short-term measurement campaigns and laboratory and controlled field testing. However, they are limited in their ability to capture spatially distributed structural behavior in real time.

Single-point scanning LDV are the natural evolution of single-point fixed LDV by which the laser scans the surface of the object by means of a set of mirrors. The measurements of all the points are synchronized to the same data basis and therefore it is possible to perform modal analysis. This technique **does not allow however performing measurements of transient phenomena**, such as the deflection of a bridge with traffic.



6.3 Simultaneous multi-point parallel LDV

Recent advances have enabled multi-point, scanning, and parallel LDV systems capable of:

- Simultaneous measurements at multiple locations
- Real-time capture of mode shapes
- Full-field vibration mapping

These systems are particularly suited for large civil structures, where spatially dense measurements are required for advanced SHM and digital twin applications.



Figure 5: multipoint simultaneous LDV

7. Comparison of LDV with Conventional Sensors

The following table summarizes the comparison of PDV and accelerometry:

Aspect	Laser Doppler Vibrometry	Accelerometers
Measurement principle	Optical, non-contact	Contact-based
Installation	Remote, rapid	Intrusive, time-consuming
Low-frequency performance	Excellent	Limited
Mass loading	None	Present
Spatial scalability	High	Limited by cabling
Long-term maturity	Emerging	Well established

8. Practical Considerations and Limitations

While LDV offers significant advantages, several practical factors must be considered:

- **Surface reflectivity:** Concrete and steel generally provide adequate reflection, but retroreflective coatings can significantly improve signal quality.
- **Line-of-sight requirements:** Optical access must be maintained between the sensor and the structure.
- **Environmental effects:** Atmospheric turbulence, rain, fog, and dust can affect signal quality, particularly over long distances.

Modern LDV systems mitigate these issues through coherent detection, advanced signal processing, and high sampling rates.

9. Integration with Digital Twins

LDV is particularly well suited for digital twin development and model updating, as it provides:

- Dense spatial measurements
- Accurate low-frequency dynamic data
- Measurements under real operational conditions

This enables improved calibration of numerical models, validation of boundary conditions, and development of predictive maintenance strategies.

Example 1: The case of La Marota viaduct (Spain)

This case presents the use of a **Ommatidia's Q1s laser radar** for non-contact vibration monitoring of the La Marota high-speed railway viaduct in southern Spain. The work is part of a multi-year structural health monitoring (SHM) program of ADIF (owner of the railways in Spain) and was performed by a consortium Universidad Politécnica de Madrid, INES Ingenieros, T-Wave and Ommatidia Lidar.

The La Marota Viaduct is a 380 m long continuous concrete box-girder bridge with nine spans, designed for high-speed rail traffic up to 300 km/h.



Figure 6: La Marota viaduct

Experimental Validation

4 LDV (Ommatidia Q1s) were hung from three pillars of the viaduct looking upward to the lower surface of the deck:



Figure 7: Installation of the LDVs under the viaduct

Each of the LDV can capture **128 simultaneous points**, so the whole deck between two pillars can be captured.

Laser vibrometry measurements were compared against accelerometer data at mid-span, showing strong agreement in time histories and frequency content.

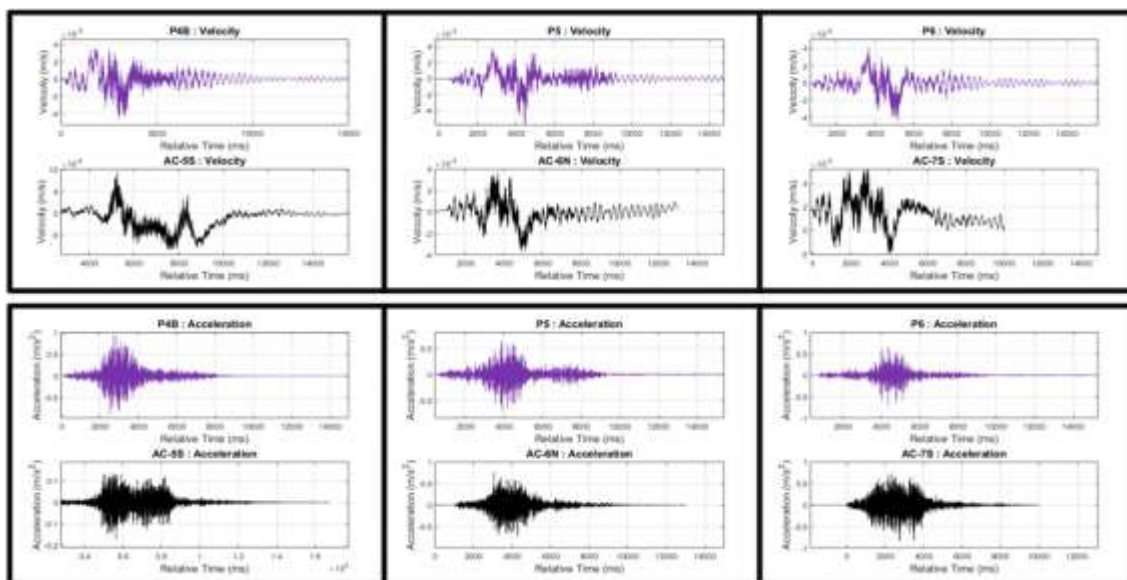


Figure 8: comparison between accelerometers and LDV at different point under the deck

A 3D beam finite-element (FE) model was developed and calibrated to represent its dynamic behavior, including realistic boundary conditions and non-structural masses. The numerical modal frequencies showed good agreement with experimental results.

For real train passages at 260 km/h, the difference between numerical and experimental values was **below 5%**, confirming the accuracy of the optical system. Additionally, relative displacements obtained by integrating LDV velocity signals matched closely with FE model predictions, even at very low frequencies.

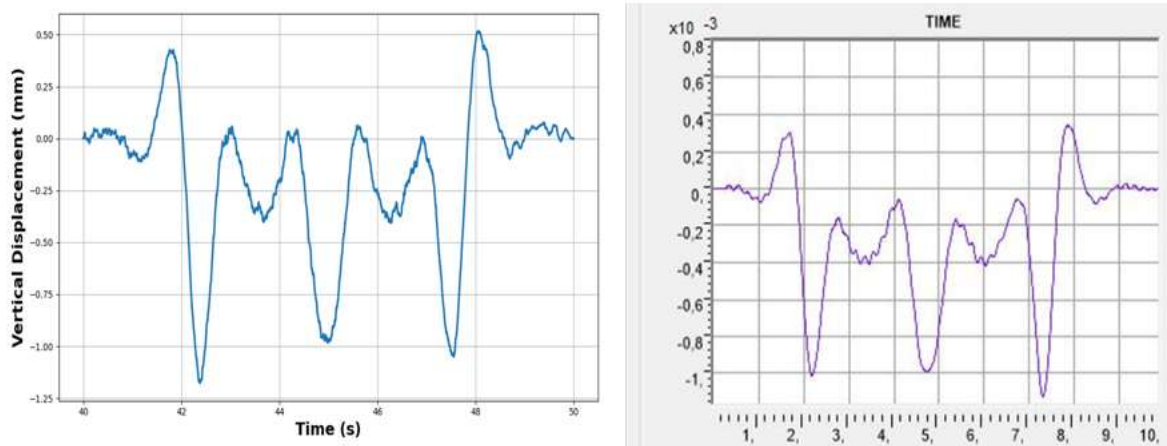


Figure 9: Comparison between the measured (left) and calculated (right) deflections of the central point of the deck at the passage of the train

Example 2: Eigenfrequency measurement of a foot bridge in Madrid (Spain)

The footbridge under test was in the district of Santa Eugenia, Madrid, Spain. It is a very slender steel structure around 42m long and 1.5m wide built in the 1980s. Pedestrians complain that the footbridge “is shaking a lot”, so the city hall has contracted a company to perform an expertise.

The tests were carried out on 27/11/2025. Road traffic and pedestrian traffic on the walkway **were not interrupted**, nor was it necessary to wire or paste sensors. The total duration of the measurements from arrival to finish was 30min. The Doppler laser vibrometer was located under the dashboard on the side of the road in the direction of Madrid (Figure 1). The bridge was excited by 3 workers jumping over the walkway over the median.

Figure 1: Position of the laser vibrometer under the walkway.



Results were measured over 40s. The main takeaways are:

- V_{\max} : 52mm/s
- D_{\max} : +/-2.6mm
- A_{\max} : 1.2 m/s²
- Modal oscillation frequencies: 2.7Hz and 3.6Hz

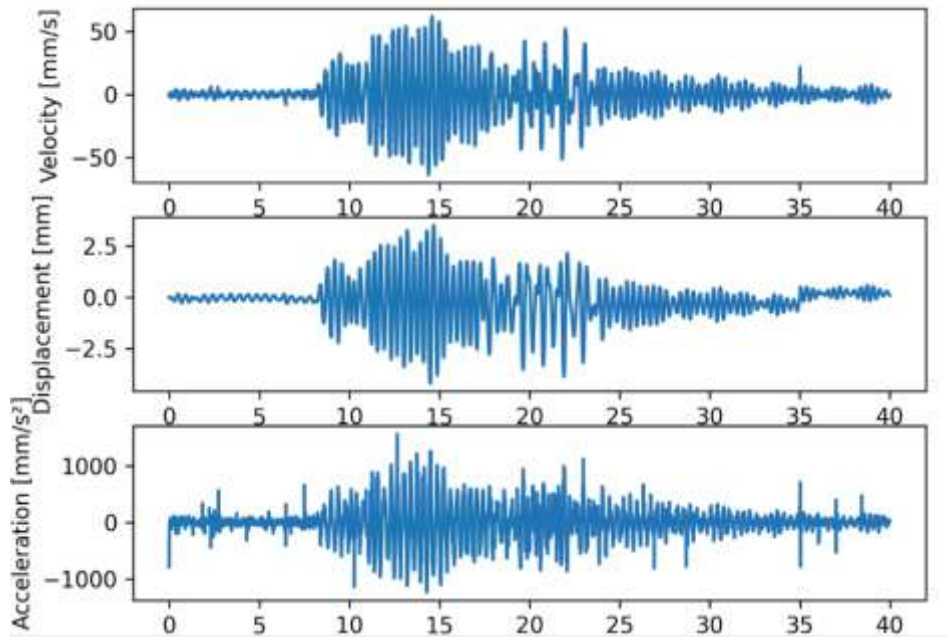


Figure 10: Temporal measurements of velocity, displacement and acceleration.

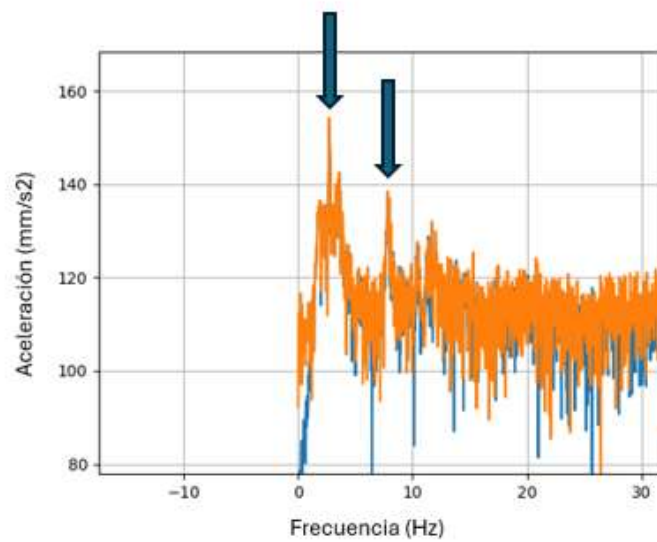


Figure 11: FFT measurement of the acceleration (mm/s²) of the oscillation of the center point of the walkway. The peaks are at 2.7 Hz, and 3.6 Hz

Example 3: Real-time measurement of a bridge in Tres Cantos (Spain)

In another recent field test, we deployed a **Q1s LDV** under a bridge in Calle de la Hierbabuena, Tres Cantos, Spain, in order to monitor the deflection profile of a road bridge under live loading.



Figure 12: Google Maps view (left) and image of the bridge(right)

The deployment of the unit takes just some minutes, and the only equipment involved is the sensor head, the tripod, the computer and the batteries. The Q1s was placed under the bridge, on the plane of the axis of the bridge, and with the 128 parallel channels aligned also along the axis of the bridge pointing **along the axis of the lower surface of the deck**.

Ommatidia has developed a specific software **Deflection Sense™** that allows measuring the deflection in streamlined way and in real time so that decisions can be taken on the spot. This software exploits the unique capability of Ommatidia's instruments to combine laser radar (i.e., distance measurement) and laser Doppler Velocimetry.

Deflection Guard™ software works as follows:



1. First, the user enters the distance from the Q1s unit to each of the pillars of the bridge (in our case, 5m and 18m) and the height of tripod (0.9m in our case).
2. The user selects the time lapse between the measurements that will be shown in the screen. In a back process, all data are measured at a frequency of 50ms, so all data (an even a video) can be recovered after the measurement.
3. When the measurement starts, the first measurement in **laser radar** mode is taken. The instrument measures the absolute distance of each laser spot to the instrument. With this data the software calculates the height of the bridge (3.5m), the X coordinates and the height at each measuring spot. This first laser radar measurement will be taken as the baseline to compute the relative vertical displacements (Figure 3, up).
4. Then, the software passes to velocimetry mode for the rest of the measurement. The reason for this is that the velocimetry mode is intrinsically more sensitive to movement than the radar mode. In velocimetry mode, the unit can measure velocities down to 10 nm/s with an integration time of 25µs (i.e. theoretically $25 \cdot 10^{14}$ but in real terms more in the range of 1pm), while in radar mode the typical resolution is around tens of microns. This allows for the measurement of very small displacements as seen in Figure 3 (down).

The results in Figure 3 were obtained during the passage of a truck (live traffic) over the bridge. They show that the maximum deflection of the bridge was around 0.3mm.

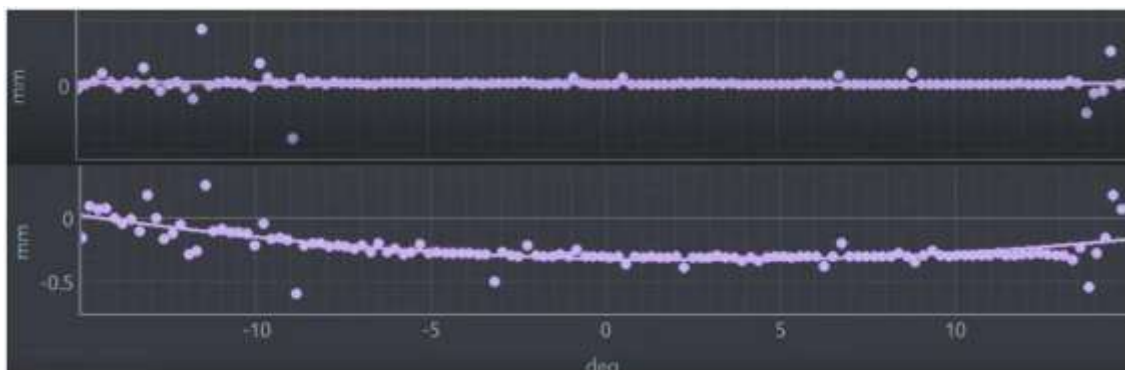
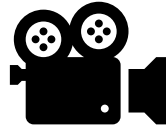


Figure 3: Deflection Guard™ Software for bridge deflection monitoring in two times: at the beginning, unloaded bridge (up) and fully loaded bridge with a truck)

A real time video of the measurement can be seen in the following link, click below:



[▶ Play Vídeo](#)

* If the link doesn't open, copy and paste this URL into your browser:

https://youtu.be/uXXeLY_2daU

Agreement with numerical models and conventional sensors highlights its potential for **advanced structural health monitoring and predictive maintenance of critical infrastructure**.

10. Conclusions

Laser Doppler Vibrometry represents an emerging and powerful sensing technology for the structural health monitoring of bridges, viaducts, towers, and buildings. Its non-contact nature, high sensitivity at low frequencies, and ability to provide spatially dense measurements make it a strong complement or alternative to traditional sensor-based SHM systems. As multi-channel and permanently deployable LDV systems continue to mature, LDV is expected to play an increasingly central role in advanced infrastructure monitoring and digital twin frameworks.

Do you need more information?

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