RECENT PROGRESS IN DIAGNOSTICS OF CIVIL STRUCTURES BY LASER VIBROMETRY

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Abstract: One of the main difficulties of drawing maintenance plans, or choosing interventions necessary to stop the growth of pathological mechanisms regards the determination of an objective and repeatable way of assessing the conservation state of civil structures. At present, we still generally proceed by sight analysis, or perform just some measurements in selected spots to derive information about the static/dynamic behavior of the structure. Also the diagnostic intervention is usually done after that some accident occurs and the situation looks dangerous for building users. Through the employ of a really innovative technique for non invasive diagnostics, scanning laser Doppler vibrometry (SLDV), we propose a testing protocol which can be applied to the entire cycle of construction, starting from accepting material in the building site, to arranging a specific maintenance program, and, generally, for a detailed inspection of pathologies. This technique consists in measuring, using laser instruments, the velocity of small vibrations induced in investigated surfaces by suitable excitation sources. This study is composed of laboratory tests and results collected during a number of surveying campaigns on buildings of special interest.

Introduction: In this work we will illustrate the use of SLDV for the diagnostics of civil and historical buildings, with a special consideration for an increasingly diffused type of façade covering, the so-called ventilated claddings, in brief ventilated walls. Ventilated walls (Lucchini 2000), represent an innovative system of building cladding that is quickly spreading in the international market for a series of well demonstrated advantages: superior technical behaviour, easier maintenance operations, and aesthetic qualities. Ventilated walls greatly decrease thermal dispersion of buildings, at the same time furnishing a barrier to external noise and a better response to cracks developing on any covering surface. On the other hand, these indisputably desirable features require a greater attention to all aspects of ventilated walls installation and a continuous monitoring during all the slabs life cycle: careful choice of constituent materials, low tolerances in slab dimensions, tight control during walls mounting.

In reference to ventilated walls and other cladding systems using mechanical anchorage - there is, to date, no diagnostic technique capable of identifying fissuring and loosening phenomena, with the exclusion of manual beating. Thus, in order to know the state of preservation of the facing, one must proceed with a punctual mechanical operation carried out by specialized personnel, on the basis of which the entity of the damage can be evaluated. However, one generally turns to manual beating technique once damage has already occurred and there stands an high urgency of safety measures.

This situation is quite common in the building industry, although sophisticated monitoring and diagnostics techniques have been proposed (Wenzel, 2001). Different measurement techniques and approaches, Peak-picking, Least Square Method, Stochastic Subspace Identification, Modal Analysis, damping ratio calculation by Random Decrement, allow the extraction of the dynamic characteristics of the civil structures from vibration data. These characteristics serve as input to mathematical models of the structure to fine tune them and to identify and assess damages. It is thus crucial to precisely measures these vibration data, possibly remotely so not to alter the examined object in any way.

In this respect, at the Polytechnic University of Ancona an innovative approach based on laser Doppler vibrometry has been developed and patented (Castellini et al. 1998), to perform contact-less acquisition of diagnostic data and to detect slabs loosening, cracks and micro cracks developing in ventilated walls. Proposed technique employs acoustically induced vibrations of slabs, and thus constitutes a diagnostic technique which is totally non invasive in terms of both the measurement sensor (laser beam) and the excitation (sound waves). We will present a series of results collected in Milan and also present other applications of the SLDV emerging in the assessment of civil and historical structures.

For this scope, two sample brick walls have been constructed in the University labs and their vibrational behaviour fully characterized by SLDV before and after some damage has been induced. Important variations in resonance frequencies have been individuated, while in a similar study conducted on a small rural building the presence of cracks has been clearly revealed.

Moreover, an example of vibration monitoring of historical monuments will be presented, as we recorded the varying response of a Roman villa columns in Pompei to the vibrations induced by a portable electric power generator.

Finally, during all our experiments and in situ measurements, the problem of effectively exciting the structures has emerged as one of paramount importance. There exists the possibility of using environmental vibrations (Wenzel, 2001), but we do prefer active excitation due to better repeatability of measurements and completeness of excitation spectra. We already mentioned the use of acoustic sources but they cannot be used to generate very low frequencies, so other types of exciters have been employed, namely a road vibratory plate compactor. In this case arises the issue of isolating the SLDV from ground vibrations and some form of solution will be shown.

SLDV technology: The SLDV may accurately measure point-by-point surface velocities using interferometric techniques and a couple of galvanometric driven mirrors steering the laser beam. In this way it is possible to scan a grid of acquisition points acquiring response spectra and time histories of the velocity of each point; these data are then processed and presented as 2D or 3D colour maps. Modern SLDVs may scan 100 points/second for a total number of more than 100,000 points working with a maximum frequency in the range of some tens of MHz, and with a lower limit of less than a Hertz. These features make the SLDV an ideal instrument in applications where it is impossible or very difficult to use standard vibration measuring devices, such as accelerometers. For example, this happens with distant structures, a common situation encountered in the building industry sector. Moreover, accelerometers will load the examined structures and may even damage delicate surfaces and, to perform an accurate vibrational analysis, it would require to employ many transducers or to move one all around the tested piece; in both cases time and cost would rise considerably.

As its own name says, this type of vibrometer uses the Doppler phenomenon to remotely acquire vibration velocities: surface vibrations induce a Doppler frequency shift on the impinging laser beam, and this shift is linearly related to the velocity component in the direction of the laser beam. In this way we have established a linear connection between laser beam frequency variations and velocity values. The obstacle facing us now is that Doppler shifts are usually very small when compared to the laser fundamental frequency, typically 1 part out of 10^8; the only way to appreciate such small quantities is to use interferometry, so that high frequency oscillations are combined and reduced to much lower values that can be dealt with by standard electronics. A scheme of a vibrometer incorporating a Mach-Zender interferometer is presented in Figure 1. Laser emission is split in two equal power beams by beam splitter BS1, and, while one beam is focused on the vibrating object, the “measuring beam”, the other one stays in the laser head and becomes the so-called “reference beam”. After being reflected, the measuring beam re-enters the laser head and is recombined with the reference beam. Surface displacement varies the optical path difference between the two laser beams and this results into a phase lag varying with vibration velocity v. So we have a time varying phase difference corresponding to an instantaneous frequency component that follows v. This frequency shift is equal to the Doppler shift (f_D) and we know from basic physics that f_D depends on v and source wavelength (λ): $f_D \propto 2v/\lambda$. Demodulating this FM Doppler signal it is possible to extract the amplitude of v, but we still lack the information on the direction of the surface displacement. To solve this problem there exist two solutions, based on electro-mechanical-optical shifting of the frequency of the reference beam by a Bragg cell (like in Figure 1), or on electronic manipulation of the recombined beams.

Most diffused SLDVs have a maximum velocity range of 10 m/s, with a frequency upper limit of 200 kHz, a resolution of about 1 μm/s and a base accuracy in the order of 1%-2% of RMS reading. Laser power is less than 1 mW, so that no special safety measures are required, but nevertheless also with such low power levels working distances of some tens of meters are possible with a spatial resolution of 1 mm. All SLDV systems are governed by an industrial PC and results are stored in digital formats like BMP and JPG images, AVI movies, or UFF and TXT text data files. Moreover, results maps may be superimposed on images of the structure recorded by the internal CCD camera that always equips SLDVs.

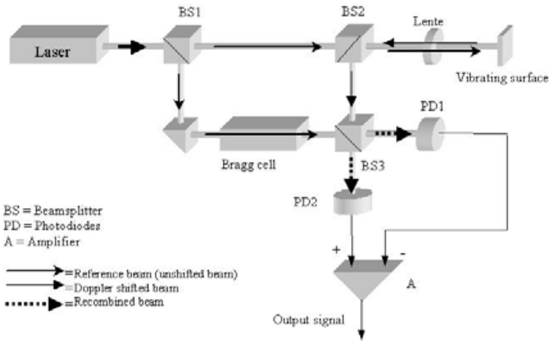

Figure 1 – Scheme of SLDV.

Generally speaking, the application of SLDV to the problem of the diagnostics of ventilated walls facades, or other building structures, is based on the well established principle that it is possible to evaluate the structural state of an object from the examination of its vibrations. The procedure of defects identification is thus basically configured as the analysis of the signal obtained from the sample facade. We may have RMS analysis, to obtain a point-to-point average value of the slab velocity, or FFT analysis, to get spectral information on each scanned point. There also exists a third approach, the so called LOCK-IN (or Fast Scan, depending on the commercial name used by different manufacturers); in this case we employ a single frequency excitation and we rapidly acquire maps of the resulting vibrations in terms of amplitude and phase. The LOCK-IN usually follows and RMS and FFT study and is used to trace much detailed maps. Usually, structural excitation is done by acoustic waves radiated by high power loudspeaker systems and doing so, we obtain a completely non-invasive measurement system, in terms of both excitation and signal acquisition. In Figure 2 we show a scheme of the measurement set-up, which is composed of the above mentioned SLDV and loudspeaker systems, plus additional instrumentation such as a sound meter to monitor emitted sound level.

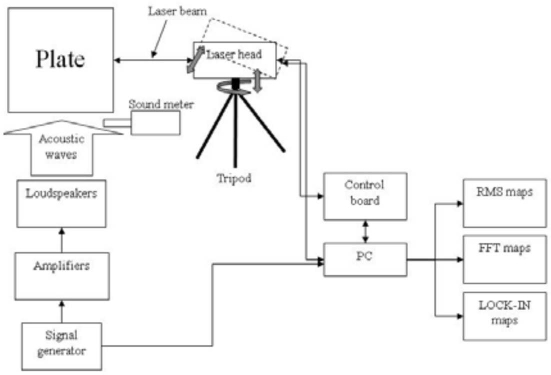

Figure 2 - Measuring set-up employing SLDV to test ventilated walls.

Results: First series of results were obtained at the sites of the JWT building and Milano Centrale head office, both of them in Milan, Italy. In Figure 3a we have a photo of the vibrometer in front of the JWT site, where we may observe the precious “santafiora” stone plates that constitutes the ventilated facade, kept in place by stud supports; unfortunately, this beautiful cover has shown dangerous loosening of some elements after a few years from its completion. In Figure 3b and 3c we report the results obtained after two single frequency scans (LOCK IN scans) at 51.5 Hz and 91.5 Hz, with the laser head positioned at about ten meters from the façade, while the loudspeakers were at about five meters. Also the Milano Centrale building has been recently completed, but already shows evident signs of degradation; a greenish biological patina is clearly visible, but also loosening of the slabs long steel supports and numerous cracks in correspondence of the cramps (Figure 4a).

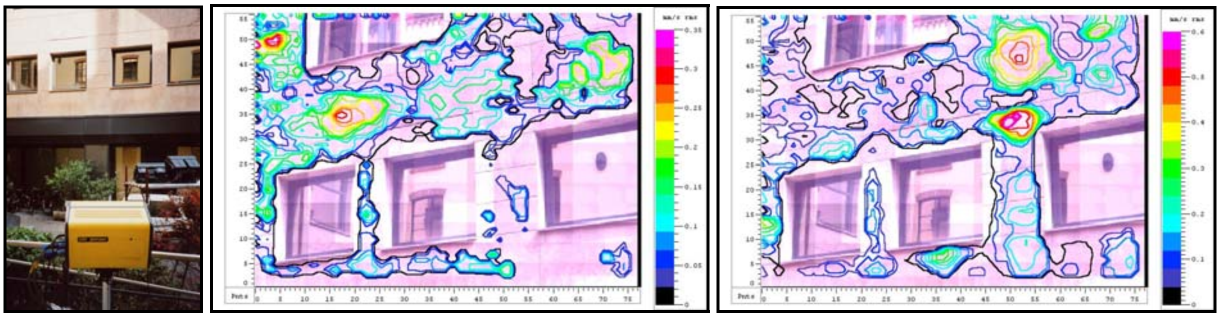

Figure 3 – a) SLDV in front of a wall b) scan at 51.5 Hz c) scan at 91.5 Hz.

In this case we investigated the plates by a single point LDV positioned at four meters from the wall and a small hammer to test the employability of this cheaper version of the vibrometer. In Figure 4b we show a drawing of the examined plates with impact (E) and recording (C) points, while in Figure 4c we have a sample of acquired frequency responses.

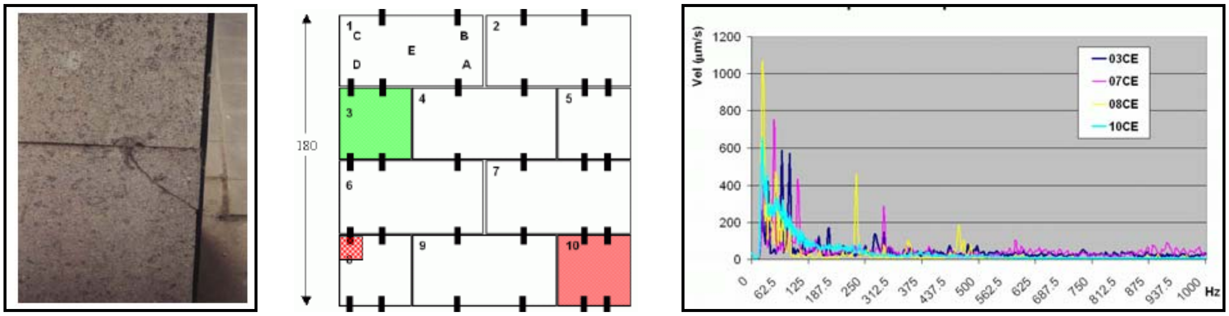

Figure 4 – a) detail of the ventilated wall b) scheme of examined slabs c) frequency spectra of plates.

To start testing the possibility of using SLDVs on civil structures, in a laboratory of the University two brick walls have been built, as depicted in Figure 5. Both walls have been excited by acoustic sources and by using a pneumatic drill, see Figure 6. In the first case, the reference signal has been provided by the white noise used to drive the loudspeakers, in the second case, an accelerometer has been placed close to the drill, with the laser head positioned at about four meters in front of the walls. After this first measurement by SLDV, both walls have been damaged by hitting them with a heavy hammer, creating an irregular groove with a width of some centimetres and a depth of about two centimetres, see dark area in Figure 7. Measurements using the SLDV have been repeated and finally in Figure 7 we show a sample of the results: we may clearly observe how the same vibration mode shifts from 77.5 Hz down to 57.5 Hz after the wall has been damaged; this result is also confirmed by the spectra in Figure 8, where other important modifications of the frequency responses are clearly observable.

After this first test in the University lab, a small building has been individuated in the country to the south of Ancona as the first test site to verify the applicability of SLDV to the diagnostics of civil structures, using a set-up very similar to the one employed in the laboratory. The structure is abandoned and presents many important cracks, especially in the front side. A photo and a drawing of the house are reported in Figure 9, while the SLDV mounted on an isolation platform and the plate road compactor used as exciter are shown in Figure 10. Also in this case an accelerometer has been used as the reference sensor placed close to the mechanical exciter. In Figure 11 we report an image of the results obtained; there appear two large areas characterized by relatively high values of surface velocity, with a central area that is almost completely still and moreover, the two vibrating zones present an irregular edge. Comparing our findings with a visual examination of the wall and structure, we observe that the central part the scan coincides with an internal reinforcing wall, while the amplitude of the velocity of vibrations decreases where two important cracks are present (see Figure 7, yellow lines show cracks, dotted blue lines relative to reinforcing wall inside the house). Also acoustic excitation has been employed, but some problems with the loudspeaker boxes have prevented the completion of the scans.

Figure 5 – Sample brick walls (Poroton bricks, left, normal bricks, right),walls 1.8 (L) x 1.5 (H) x 0.25 (W) m.

Figure 6 – Excitation of sample walls.

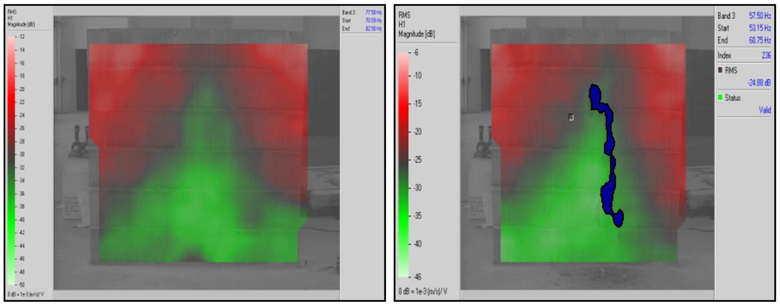

Figure 7 – Vibration maps of undamaged (left) and damaged (right) empty bricks (POROTON) wall, at 77.5 Hz and 57.5 Hz respectively; loudspeaker excitation. Black drawing identifies the area damaged by hammering.

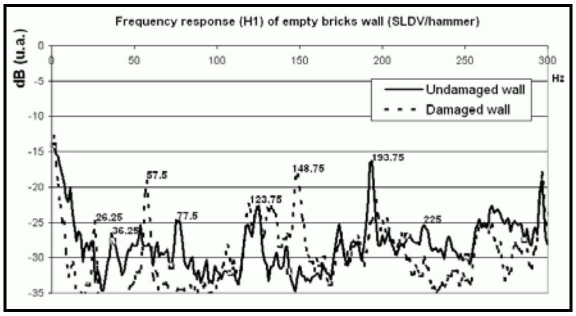

Figure 8 – Frequency responses of empty bricks (POROTON) wall.

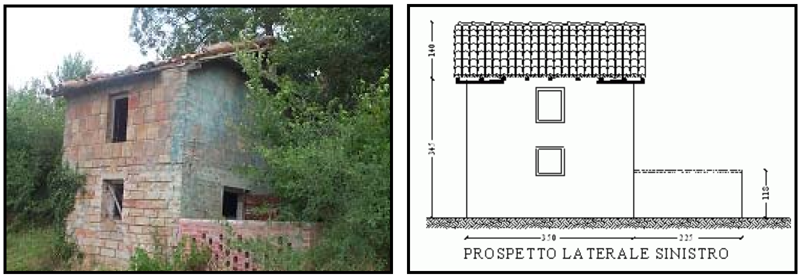

Figure 9 – Photo and drawing of examined small house.

Figure 10 – SLDV mounted on isolation platform and road plate compactor used to excite the building.

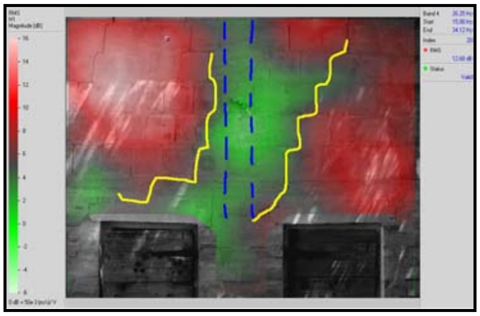

Figure 11 – SLDV scan of front wall.

As the last example of our investigations, we will present one sample of the results obtained during a diagnostic session conducted in a very famous villa in Pompei. Being no electric outlet on site, an electrical generator has been employed and a monitoring activity of vibrations induced in structural elements of the building has been conducted. In particular we have examined six columns of an approximate height of seven meters while the generator was running at different speeds due to varying electric load. In Figure 12a the laser has been aimed at column 2 and we may observe how the frequency peaks shift due to the changing rotation regime of the generator. In Figure 12b we report the results of measuring other columns, and how they show different peaks: for example, column 3 has a big resonance at 175 Hz, which is almost completely absent from the response of column 7, positioned at about ten meters from the SLDV. All columns have been measured aiming the laser at a point at about 1 meter from ground, and with the SLDV placed in a sand pit to avoid laser case and optic components vibrations that could corrupt measurements.

Discussion: Examining presented results, some observations may be done, starting with the measurements in Milan. In the JWT site some plates vibrating more than neighbouring ones are clearly evident and also other resonance frequencies have been individuated, ranging from 104 Hz for the rectangular plates with dimensions of

50x100 cm, to 51.5 Hz for the 100x100 cm square ones. The results of the SLDV have been checked and confirmed by manual beating; however we want to clarify that no plate was giving any evidence of detachment from the support or showed any crack, but we rightly spotted the plates possessing a higher mobility when compared to the other ones.

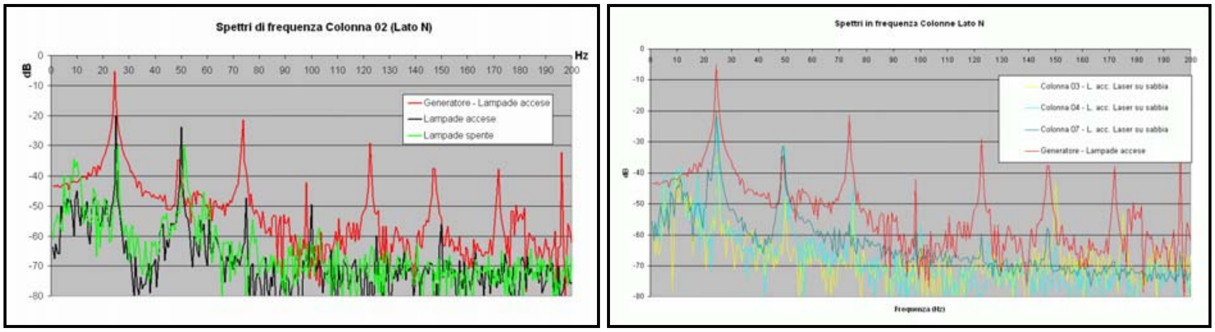

Figure 12 – (a) Frequency response of column 2 at various rotation regime of electrical generator (b) frequency response of other columns.

As regards Milano Centrale, curves in Figure 4c cannot be directly compared because we did not use a calibrated input, but nevertheless some interesting observations may be done:

1 – if we express plate mobility as an effective value obtained by the RMS summation of the spectra in Figure 4c we may indicate plate 8, followed by plate 10, as the loosest one, while plate 3 is the most stable one. This coincides with our manual findings, although plate 8 is greatly moving just in its upper left corner, where the measurement has been performed;

2 – considering our preceding experiments and measured main resonance frequencies of plates, we also determined the percentage of spectra RMS due to frequencies below 100 Hz. Percentages associated to plates 10, 8 and 3 are 94%, 93% and 85% respectively and this result puts in the right order plates mobility when compared to our manual check.

In conclusion, using single point LDV does not easily allow to find plates anomalies such as cracks or micro-cracks but we have demonstrated that even from such simple measurements it is possible to assess the adhesion state of the slabs by the observation of the amplitude and low frequency content of acquired vibrations spectra.

Tests on sample walls and on the small building demonstrated how the disclosure of defects (cracks) or important structural variations (damaging by hammer) may be done by the SLDV, although in the first case, data interpretation requires a high degree of experience by the operator.

The test in Pompei also demonstrated the capability of the SLDV to unintrusively acquire vibrational data on not-treated surfaces up to ten meters, a real asset when dealing with such precious structures. Regular monitoring of important parameters related to the state of conservation of the objects, like damping ratio and frequencies of resonance, is thus possible with no external intervention on the structure and may be performed quickly and with a high degree of accuracy. If there arises the need to put the SLDV closer to the structure, it is possible to use industrial lifters, as shown in Figure 13.

Experiments concerning the dynamical behaviour of structures have been successfully done in the lab and on a small building, but due to the high level of excitation and to the low frequencies required to excite structures, an issue is represented by the isolation of the SLDV. Different solutions have been tested, such as positioning the laser head in sand or on a heavy platform posed on rubber supports. Further studies are required, also because it is not feasible to transport heavy isolation tables. Anyhow, even the use of simple solutions like the platform in Figure 10 leads to substantial improvements. In Figure 14 we compare the averaged spectra of the vibrations of the ground close to the SLDV, of the ground close to the compactor and of the platform which the SLDV was positioned on, and we observe how the RMS level of acceleration is decreased between 10 and 250 Hz of about 13.5 dB by the use of the platform.

Figure 13 – SLDV on lifter.

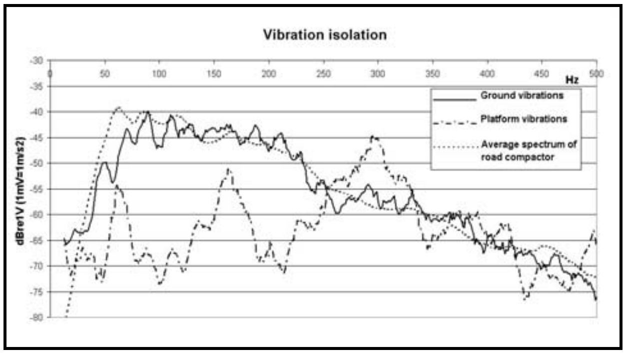

Figure 14 – Degree of isolation provided by platform in Figure 10.

Conclusions: We have presented a collection of results derived from measurement session done both in the lab and in situ, aimed at verifying the applicability of the SLDV technique to the diagnostics of civil and historical structures. In all cases, the proposed technique has been able to put in evidence a series of problems typical of examined objects, such as wall cracks and loosening plates, beside demonstrating the capability of monitoring structural components in terms of ambient vibrations. Also the fundamental issue of vibration isolation of the measuring laser device has been dealt with, proposing a first simple effective approach. However, as put in evidence by some authors (Haves, 1999, Adams, 2004) the diagnostic process is quite a complicated issue, divided between "fault detection and fault diagnosis". Moreover, to affirm that there is a fault a reference state must be known to be compared with the present situation, and also to predict structural behaviour a detailed structural model should be prepared and fine tuned using experimental data. This issue is rather important also in the planning of "any treatment that could expose the structure to unusual forces, which have the potential to disrupt its stability". The contribution of the proposed technique to this procedure is important in the sense of supplying accurate data, gathered in a non-invasive manner that completely avoids structural loading and ease also other issues like sensor placement in hazardous environments, but further studies are still needed to optimize it and to prepare a smoother integration in the other phases of the diagnostic process.

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