Laser Vibrometry Across Sectors
Non-Contact Measurement of Structural Dynamics in Civil Engineering
Application Notes

Optical Measurement Solutions for Structural Dynamics Research

Structural dynamics is an engineering discipline concerned with the behavior of structures subjected to dynamic loading. In this context a load is called "dynamic" when it creates an action which has enough acceleration to excite one or more of the structure's natural frequencies. Dynamic loads can be of any kind and include people, wind, waves, traffic, earthquakes, and blasts. Any structure can be subjected to dynamic loading. Dynamic analysis can be used to find dynamic displacements, time history, and perform modal analysis.

To understand structural dynamics phenomena, vibration measurements are essential and therefore appropriate measurement technology is needed. This is due to the fact that the dynamic load can excite vibrations in a machine or structure, which in many cases can cause unwanted effects such as premature fatigue, excessive noise, uncomfortable user conditions, difficulties with control, accelerated wear, reduced performance, poor quality perceptions …

Polytec provides a broad range of optical non-contact vibration measurement systems which are in many cases the ideal solution for the study of structural dynamics phenomena. Polytec's non-contact laser vibrometers are of enormous value for civil engineering application tasks such as those described in this brochure, as they allow a highly precise measurement of low frequent vibrations and displacements in the micrometer range over long distances. The non-contact measurement method allows a quick and easy setup without mounting and cabling of sensors on the structure, which is time consuming and often even difficult and dangerous.

Using laser-based vibration measurement, the calculation of tension forces in cables can be achieved quickly, with little work, and with the highest accuracy possible.

No Highwire Act

There are many obvious advantages that cable-stayed bridges have over other types of bridges. Some of the reasons behind their great popularity are their cost-efficient construction and attractive appearance. However, the main structural elements holding the deck in place are the stay cables, which in most cases are not thoroughly inspected over the years.

Due to corrosion, slippage, or settlement of all or part of the structure, load imbalances may occur which can have a negative impact on the service life of the bridge. Other events such as impacts, fire or seismic movement can have a significant effect on cable force distribution, influencing the fatigue life cycle of the cables. Polytec and Metro Testing have successfully used systems to provide non-contact laser-based vibration analysis services to bridge engineering firms and bridge owners – providing information about the tension forces in each cable of the structure.

Since the testing method is non-contact and non-invasive, there is no need to attach an instrument to the cable or even to have direct access to the cable being measured. A laser vibrometer (Figure 1) is located on the bridge deck with which the engineer is shooting onto the third-point of the cable. The instrument measures the reflection returning from the remote location back and compares the light signal to the reference light signal from the instrument. With an optical element, the interferometer, the instrument is able to measure very small movements at the target location. This allows the engineer on site to measure areas or objects which are impossible or difficult to reach by usual means for the determination of the velocity or displacement experienced at the laser target location.
Since no special mounting equipment is required on the bridge deck, measurements can be done quickly and efficiently, with speeds of up to six minutes per cable. Thus, using this testing method, in good weather conditions, ten cables can be measured in the span of an hour.

1
RSV-150 in action during the construction of the Deh Cho Bridge in Canada.

Engineering firms and bridge owners receive a complete overview of the tension forces of all the cables. Those data can be used to evaluate the behaviour of the structure.

Locked coil cables installed on the Deh Cho Bridge near Fort Providence in Canada's Northern Territories were measured during construction of the bridge. The data collected and the tension forces calculated provided vital information to the bridge engineer and erection engineering firm for the final completion of the bridge. All 24 cables were measured within a period of 4 days on site. The difficulty of this project layed within the logistics of the equipment position on the temporary bridge deck and the movement of the equipment from location to location. Two different excitation methods were used to determine the natural frequencies and in return the tension forces of the cables.
The non-contact vibration approach is recognised by the research community and its results generally match those generated by more traditional methods such as the use of accelerometers.

In addition to the advantage of being a non-contact method, no rigging equipment is required to measure at one-third or midpoint of a cable. A simple line of sight roughly perpendicular to the measurement point is all that is required to use this technology to make extremely accurate measurements quickly and easily.
Traditional methods can involve physical lift-off of the cable or strand at the anchorage; in some cases the use of jacking equipment on the bridge deck provides no option due to access restrictions or inability to access the cable strands. In most cases the cost of providing the jacking equipment and the resulting logistics and costing for such equipment outweigh the Laser based alternative. Polytec and Metro Testing Laboratories have joined forces in a bid to facilitate procurement of non-contact tension force measurements. Metro Testing has had years of experience performing structural data analysis – calculating the tension force from vibration data. Combined with the long range non-contact vibration measurement offered by Polytec using its laser interferometer, it can offer fast and accurate results.

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Ancient building in the Fendigasse (Vienna)

Measurement-based Demonstration of Efficiency of Upgrading Measures on Ancient Houses in Vienna

Earthquake-proof Buildings

Houses that were built somewhere between 1850 and 1914 („Gründerzeit“) have gained attention in Vienna. These valuable buildings are threatened due to the introduction of the Euro Code 8 standard (2009), which requires proof of earthquake safety during structural measures. The required detection methods are ill-suited for the modeling of this highly dynamic process and are prone to unfavorable results. As a result, the earthquake safety proof will probably fail for houses built before 1970.

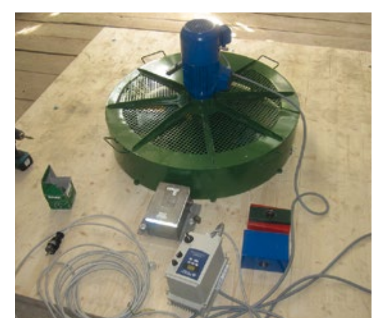
In the framework of the SEISMID® research project, a series of Gründerzeit buildings have been investigated upon their dynamic behavior during earthquakes. The project included analyses on brick and mortar samples as well as the development and calibration of finite element models. A special issue was the measurement-based proof of upgrading measures provided by using both BRIMOS®-Wireless and Polytec PSV-400 Scanning Laser Vibrometer systems. Enhanced measurements by the PSV-400 created a significant added value, because the impacts of upgrade measures could be impressively demonstrated just a few seconds after the measurements.

Object under Test and Experimental Setup

The work focused on a particular building in the Fendigasse (fifth municipal district at Vienna) which was selected for a refurbishment.

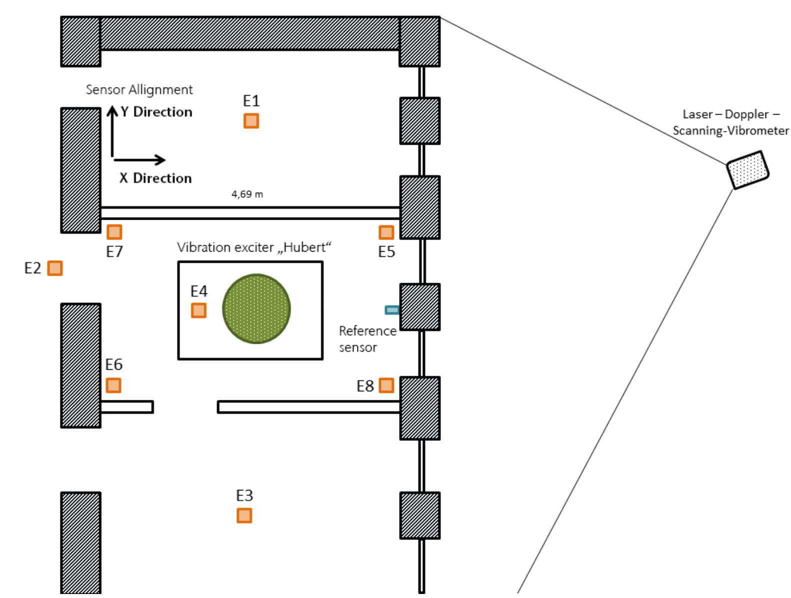
This object offered the opportunity to specifically examine various stages of renovation and upgrading. Special emphasis was placed on interior walls and wooden ceilings, as well as on the dynamic behavior of the structure as a whole. With the aid of the Scanning Vibrometer the velocity field of a structure can be determined, visualized, and analyzed. The measurement points must be visible from the observation point and must be accessible within the scan angle oft he sensor head. To be able to relate the series of measurements to each other, a reference sensor at a representative fixed point of the building is required. The measurements were performed both at ambient excitation, and when induced by a special vibration exciter that had been jointly developed by the project partners ("HUBERT", Figure 1).

Figure 3 shows the layout of the test setup for the measurement of the entire building. The exciter was located on the 4th and 5th floor and was operated at frequencies of 4.75 Hz and 11.75 Hz. The PSV-400 laser sensor head was placed on the pavement edge in order to affect neither traffic nor pedestrians (Figure 2).



1
Vibration exciter "HUBERT"

2
Laser sensor head of the PSV-400 Scanning Vibrometer



3
Layout of the test setup

Remedial Measures and their Impact
In the course of the restoration work, the following upgrading measures (1 - 7) were monitored. Figures 4 and 5 show the deflection shapes of the measurements in a given state with the maximum deflection at the excitation frequency 4.75 Hz and 11.75 Hz.

1. Unchanged original state: This measurement was used as a reference measurement, thus all of the upgrading measures could be assessed quantitatively.

2. The ceiling beams were braced with the outer wall by means of threaded rods. Thus a direct connection between the ceiling and the wall was established. Previously, it was assumed that the ceiling would respond to the excitation like a single disc, independent of the outer wall. This was proven by the measurement as well.

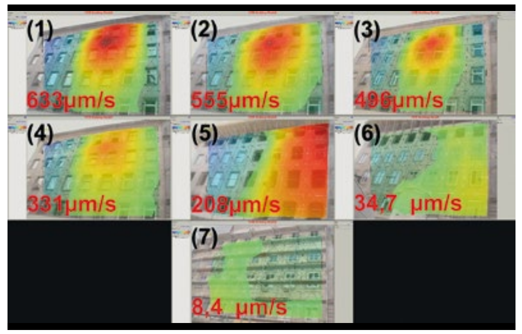
3. Balk clamped by the adjacent partition walls with threaded rods, which causes a direct connection of the ceiling of the adjacent rooms.

4. OSBs (oriented strand boards) screwed to the ceiling (from above or from below). This measure effects an increase in the shear stiffness of the ceiling.

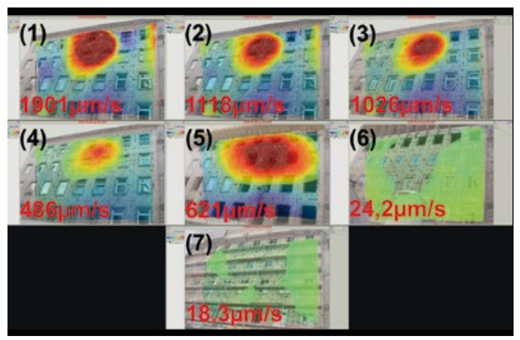
5. Concrete slab poured in the attic. After this step, a slight decrease can be seen due to the additional mass in the upper part of the structure observed in relation to the maximum vibration velocities in the range of 12 Hz. In return, the building responded to the local homogeneous excitation.

6. Fire walls were introduced for drawing fire from the basement walls to the roof, which can be described as a concrete slab. This measure had a particularly high impact in terms of vibration velocity response.

7. Final state: concrete and steel structures finished, ceiling windows reinforced in the 3rd and 4th upper floor. A further decrease in the vibration velocities can be determined during analysis of the measurement.



4
Vibration modes at 4.75 Hz. Excitation after different reinforcement measures (1 - 7).



5
Vibration modes at 11.75 Hz corresponding to excitation.

Conclusions
Because the effects of structural changes can be represented graphically within a few seconds after the measurement, PSV-400 Scanning Vibrometer results offer significant value for the metrological impact of remedial measures to Historicist style buildings and houses.

Measurements are especially excellent on the outer facade after the modifications have taken place.
The individual steps produce a partial redistribution of the vibrational energy to several parts of the building. The maximum effectiveness, however, is only achieved if all measures are set at the same time. To conclude, it is relatively easy and at the same time inexpensive to significantly improve the vibration behavior of the building during an earthquake.

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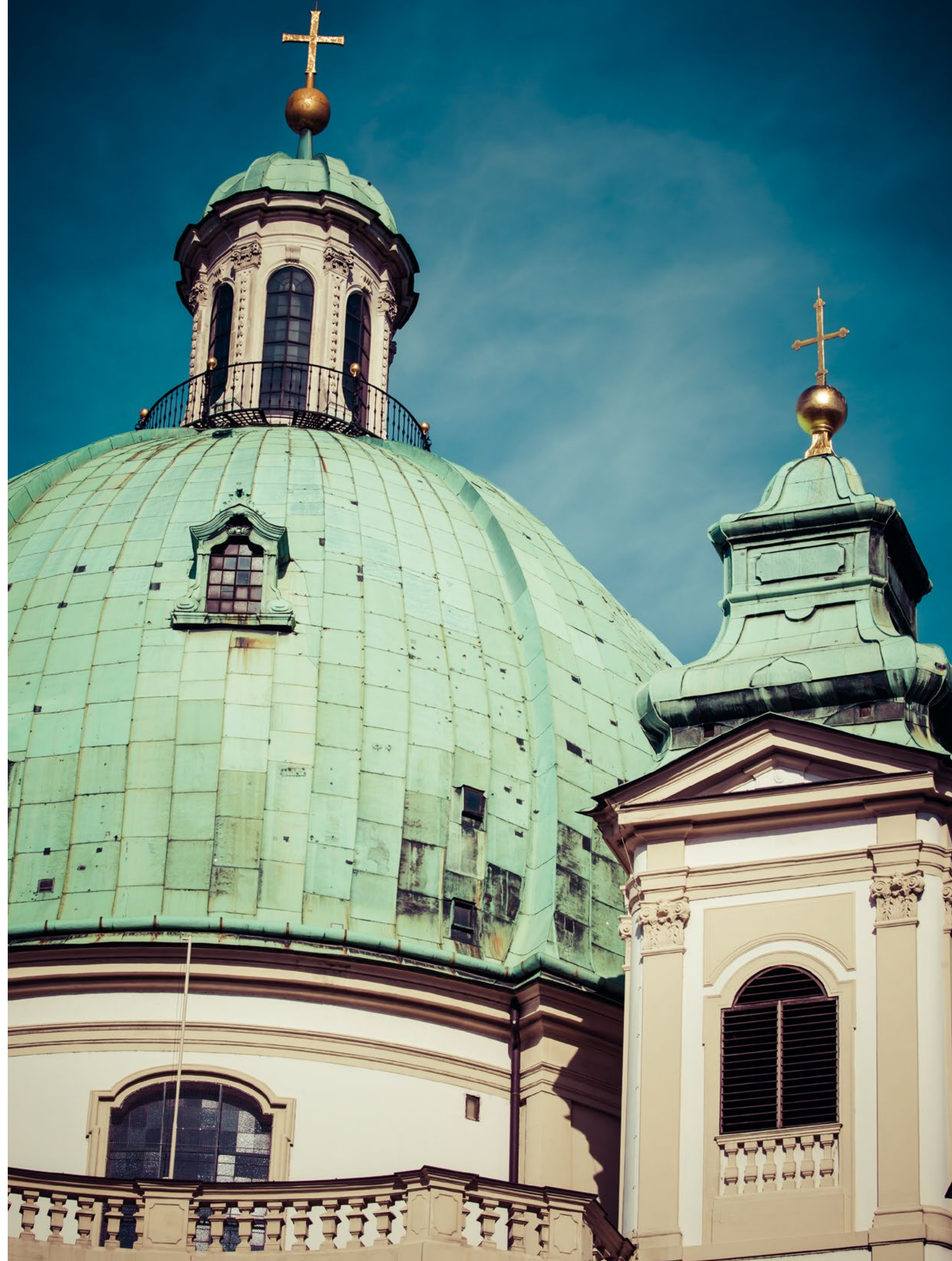


Safety for Sustainable Energy

The design specifications and maintenance protocols of wind power plants must assure that the mechanical limits of the components are not exceeded. In operation, the wind excites vibrations in these plants which can lead to dynamic deflections of the tower and the rotor blade of up to 1 meter with typical eigen frequencies of several Hz.

Wind power plant vibrations must be monitored during operation to optimize the simulation models used for design and construction, and to ensure faultless day-to-day operation by recognizing excessive material stress and fatigue prior to failure. Such preventative maintenance, or condition monitoring, is often done with the aid of vibration sensors which are placed along various sections of the drive shaft. These sensors can then monitor vibrations and provide information on the status of bearings in the power transmission. To monitor the rotor blades is much more difficult, particularly during operation, since measuring vibrations with contact sensors is only possible when using elaborate telemetry systems.

Laser vibrometry is a non-contact, optical technique for measuring vibration with zero-mass loading. The laser probe permits a long standoff distance (remote) from the measurement point, and, in the ideal case, there is little surface preparation prior to the measurement. This investigation tested the suitability of using laser vibrometers for non-contact, remote measurement of vibrations in wind power plants. The study was within the framework of a much larger project to research sensor-enabled operational monitoring systems. This scientific work is part of the research network CEwind, in which the activities of many German universities are grouped together with the goal of elaborating and solving fundamental issues concerning future wind power plants, parks and infrastructure.

Experimental Issues

The wind power plant examined was an Enercon model E-30 with a nominal rating of 300 kW and a hub height of 50 m. Various vibrometer systems were placed at ground level and used for measurements on the tower shaft and on the rotor blades.

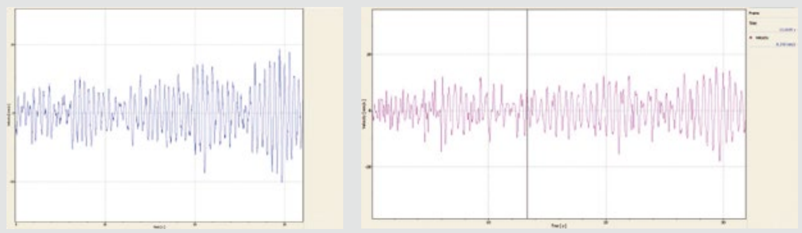
In the experiment, apart from the eigen frequencies, the signal-to-noise ratio and transmission functions should be determined for both unprepared surfaces and those prepared with reflective film. Both a rotor blade and the hub had reflective film bonded in specified places in advance (Figure 1).

For high resolution and reference measurements, an OFV-505 single point vibrometer was available. The OFV-5000 vibrometer controller was equipped with a high-resolution, digital VD-09 velocity decoder. Other measurement points were acquired using a PSV-400 Scanning Vibrometer. The scanner mirrors made it easy to align the laser to the measurement locations and with the aid of the integrated geometry scanner, it was possible to determine the coordinates automatically.

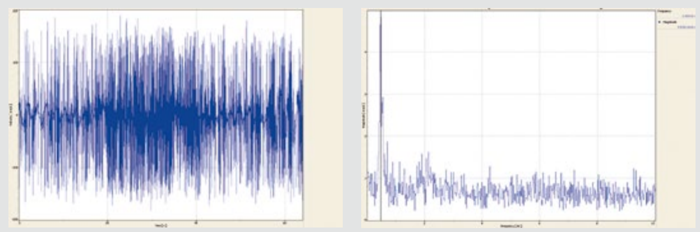
Results

Vibration measurements with a good signal-to-noise ratio can be made easily on the prepared surface, even at standoff distances of 90 m. The first eigen frequencies are at 0.47 Hz for the tower or the hub and at 1.85 Hz for the rotor blade. Without averaging, harmonics of these frequencies can be seen up through 50 Hz.
On the surfaces that have not been prepared, good measurements are also possible using the OFV-505 sensor head with an SLR Super Long Range lens. The measurement values must be limited to less than 5 Hz with a low pass filter (Figure 2). To align and monitor the measurement spot without reflective film, a telescope with a narrow bandfilter for the laser wavelength, or other optical aid, is strongly recommended. To determine the transmission function, measurements were carried out with several vibrometers at the same time on a fixed reference position, and on various points on the rotor blade. The measurements result in noise levels of 1 µm/s for the velocity signal (at 4 mHz resolution), or respectively 0.1 µm for the displacement signal. Displacement amplitudes of up to 8 mm were observed, at moderate wind forces (12 ... 28 km/hr.) during the measurements. The equipment worked well and first attempts to make measurements during operation (rotating blades) were successful. The tower vibrations are superimposed with the periodicity occurring as a result of the rotor rotation (Figure 3, left).

1
Laser spots on the reflective film on the rotor blade.



2
Time progression of the vibrational velocity on the rotor blade; Left: PSV-400 with reflective film; Right: OFV-505 with SLR lens, without reflective film, with low pass filter applied (5 Hz).



3
Measurement during operation, time signal (left) and frequency spectrum after FFT and low pass filtering (right).

After a Fast Fourier Transformation (FFT) of the signal and applying a low pass filter, the first eigen frequency of the tower can clearly be seen at 0.47 Hz (Figure 3, right). To be able to acquire the vibrations of the rotor blades during operation as well, the measurement would have to be made closer to the hub. There, the duty cycle for the retention period of the laser spot on the rotor blade is more favorable. With the aid of a time resolved FFT, it would then be possible to separate the tower and rotor vibrations from each other.

Laser vibrometers are a powerful tool for remote, non contact vibration monitoring of wind power plants or other large engineered structures. Equipped with the appropriate measurement technology and a suitable measurement setup, the measurements are easily made from the ground with the plant operating or stationary even without applying reflective film.

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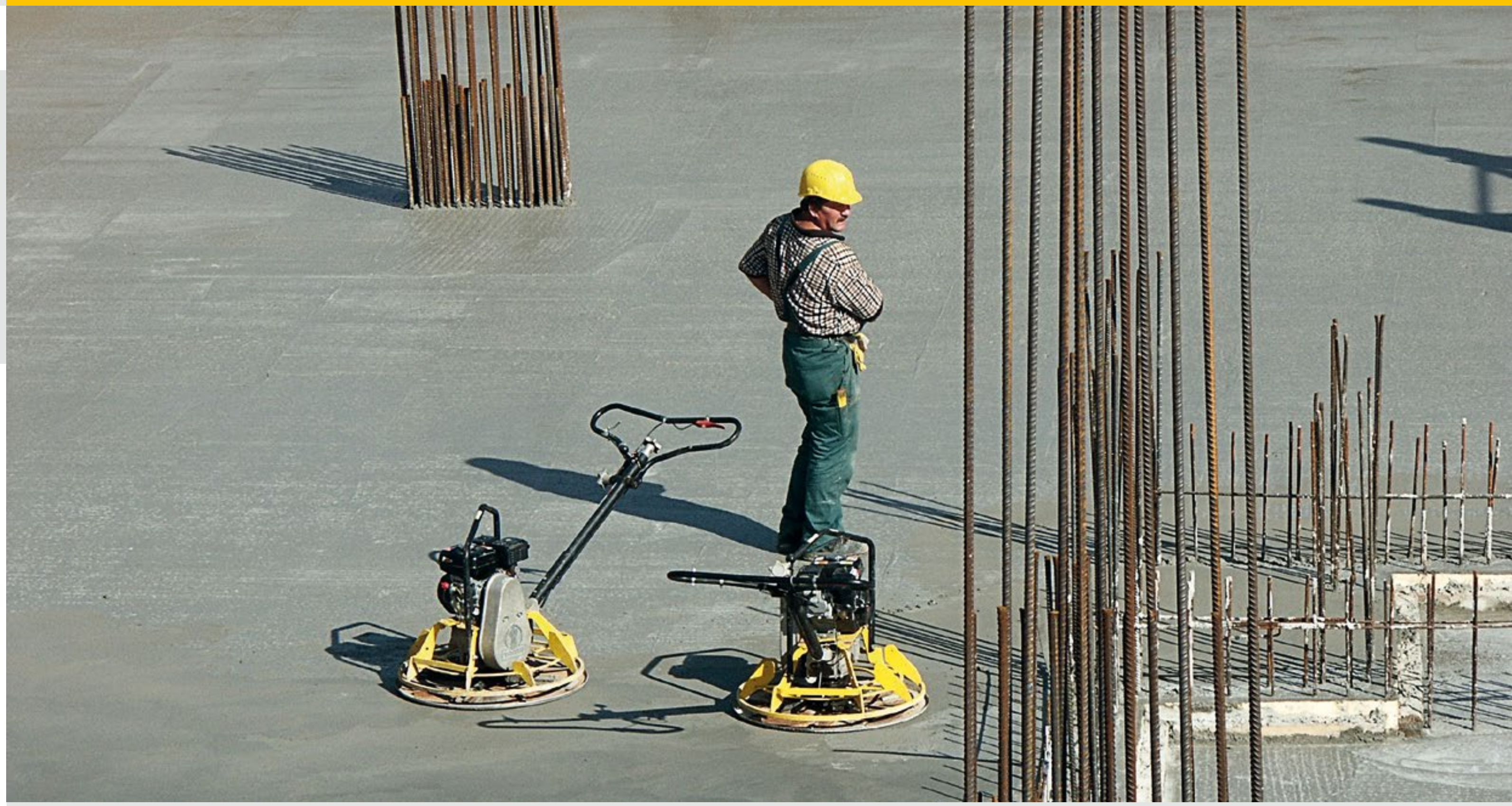
Hard as Rock



Laser Ultrasonics is a scanning, acoustic method for non-contact, non-destructive evaluation of materials. This article describes its application to cement-based materials during setting and hardening. The ultrasonic excitation is created by a small amount of ablation produced by a short-pulsed Nd:YAG-laser, and the detection on the reverse side of the sample is carried out interferometrically by a laser vibrometer. By matching the appropriate pulsed laser beam parameters to the material under study, a reproducible sound excitation was achieved. This allows the interferometric measurement of the ultrasonic pulse velocity, v_p, as well as the velocity amplitudes of the compressive wave.

An understanding of the curing process for fresh cement-based materials is essential for material research, quality control, and the practical planning and implementation of construction projects. In order to describe the material properties, the ultrasonic pulse velocity (v_p), the first amplitude of the longitudinal wave and the transmitted frequency content can be used. Immediately after mixing, cement-based materials show a significant damping effect on ultrasonic waves together with low pulse velocity. During the course of the curing process, the ultrasonic pulse velocities and signal amplitudes increase continuously. The ultrasonic pulse velocity depends on the used cements, admixtures and additives but also on the water/cement (w/c) ratio, grain distribution and air pore content. Since objects can be non-destructively investigated without contact and at a standoff distance of several meters, laserultrasonic inspection is a preferred technique for a number of specific applications. Pulsed lasers permit a contactless excitation of longitudinal, shear and surface waves directly on the exposed surfaces. The resulting velocity amplitudes are measured without contact by means of a laser vibrometer using the Doppler effect and heterodyne detection. In the following paragraphs, the principles of laser-induced excitation and interferometric detection of ultrasonic waves are described with respect to the specific experimental setup that permits the investigation of cement pastes and mortars.

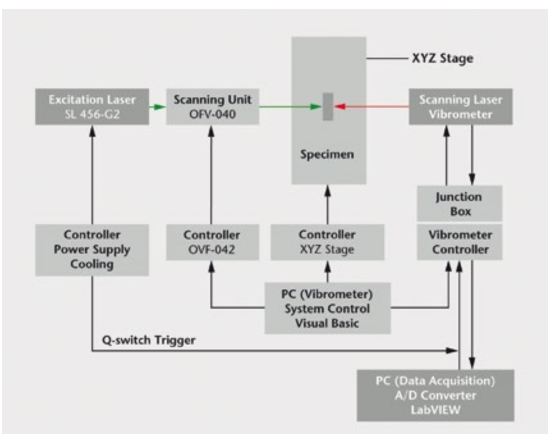
Experimental Setup

The principle hardware configuration is shown in Figure 1. For laser ultrasonic generation, a Q-switched, solid-state Nd:YAG-laser with a fundamental wavelength of 1064 nm is used (Figure 2). To characterize the excited ultrasonic waves, a scanning laser vibrometer is deployed which uses a heterodyne interferometer to detect the acoustic displacements. A sample mold with transparent walls was specifically developed for this application to allow laser-induced excitation and detection of through-transmission ultrasonic waves in setting and hardening mixtures (Figure 3). Two measuring grids consisting of 27 measuring points for excitation and detection were created and aligned opposite to each other. The data acquisition and evaluation was managed by an algorithm implemented in LabVIEW. This algorithm allows the automatic detection of the compressive wave onset and further signal parameters such as the first amplitude of the longitudinal wave and the signal-to-noise ratio.

Experimental Investigations and Results

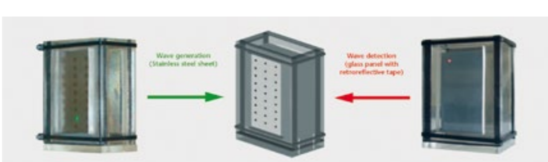
Continuous investigations on cement-based materials during the hydration process have been carried out. Further more, the local distribution of the ultrasonic pulse velocity, v_p, have been determined at definite times after mixing. Various cement pastes and mortars were investigated. Regarding the cement pastes, two different w/c ratios were applied. The mortar samples had various grain size distributions and various PCE-based superplasticizer content. In Figure 4 the development of the ultrasonic pulse velocity is shown for two cement pastes under variation of the w/c ratio. A measuring point in the center of the specimens was chosen. The laser ultrasonic measuring sensitivity is sufficient for a through transmission of these strongly absorbing systems. In the course of the curing, both experimental mixtures show an increase in the ultrasonic pulse.

The cement paste with a lower w/c ratio shows a significantly stronger increase in velocity. In contrast, increasing the amount of water will lead to a delayed and much smaller increase. In Figure 5, the development of the first amplitude of the longitudinal wave is shown as the surface displacement on the detection side. The cement paste with a lower w/c ratio shows an earlier and steeper increase when compared to the one with the higher w/c ratio. This parameter allows a continuous evaluation of hydration kinetics. As the microstructure continues to develop, the influence of shrinkage processes on the coupling conditions becomes clear.



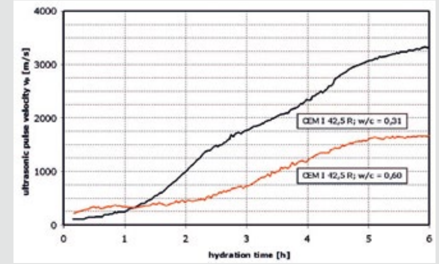
1
Laser ultrasonic inspection setup and configuration.

2
Laboratory setup: Excitation laser with scanner (right, background); positioning stage with sample (center); Scanning Laser Vibrometer (left, foreground).

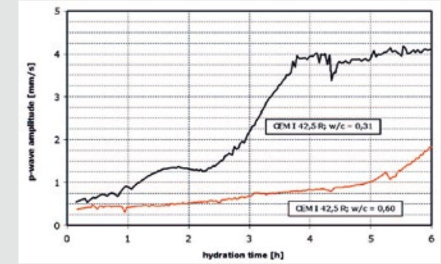


3
Testing mold for laser-based ultrasonic evaluation: front view with excitation laser spot (left); schematic view (center); back view with vibrometer laser (right).

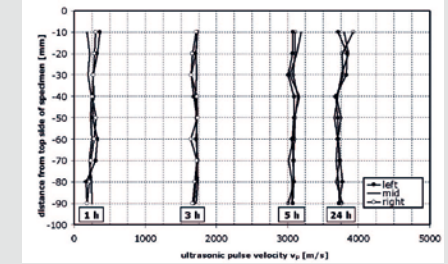
Laser-Based Evaluation of Cement Hydration



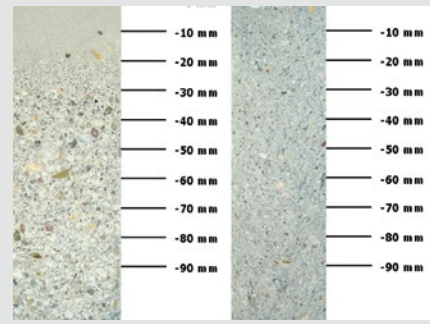
4
Ultrasonic pulse velocity vs. hydration time for cement pastes with different w/c ratios.



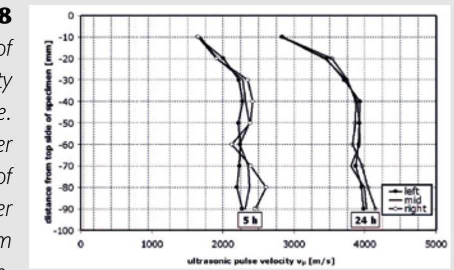
5
Evolution of longitudinal wave first amplitude for cement pastes with different w/c ratios.



6
Distribution of ultrasonic pulse velocity over a cement paste sample. The narrow distribution in velocity across the sample at any given point in time indicates that the sample is homogeneous.



7
Mortar M1 with sedimentation phenomena (left) and homogeneous mortar M2 (right) with the heights of the measuring points.



8
Spatial distribution of ultrasonic pulse velocity in a mortar sample. The trend from lower velocities at the top of the sample to higher velocities at the bottom indicates an inhomogeneous sample.

Local Distribution of Elastic Parameters

In Figure 6, the distribution of the ultrasonic pulse velocity of a cement paste with a w/c ratio of 0.31 at varying points of time after the beginning of the hydration is shown. At every point in time, similar sound velocities were determined over the whole specimen. Therefore, it can be assumed that there are no differences in the hydration progress or in the mixture composition and that the specimen is homogeneous (Figure 7, right). The comparison of the ultrasonic pulse velocities with time allows an evaluation of the hydration kinetics. The distribution of the ultrasonic pulse velocity of a mortar sample at 5 h and 24 h after mixing is shown in Figure 8. Over the test piece's height there are significant differences in the ultrasonic pulse velocities.
In the bottom part of the specimen higher sound velocities are reached which can be explained by a higher aggregate content. This is due to insufficient mortar sedimentation stability. Before stiffening, a settling of the coarse components of the aggregate takes place and an enrichment of fine mortar in the upper part. This is confirmed by the visual examination (Figure 7, left). Thus, by means of the laser-based ultrasonic transmission method, a non-destructive evaluation of local structure differences vertical to the through-transmission direction can be achieved.

Summary and Outlook

The experimental results using laser ultrasonic inspection on cement pastes and mortars show that ultrasonic through-transmission can be used for a non-destructive, contactless investigation of setting and hardening of building materials. In order to describe the evolution of the material properties, the time-dependent and local changes of the ultrasound parameters can be used. The ultrasonic pulse velocity and the velocity amplitude of the longitudinal wave allow a continuous evaluation of the hydration kinetics. Using the ultrasonic pulse velocity, it is possible to show local variations of the mixture composition of the investigated cement pastes and mortars vertical to the transmission direction. This can be used to evaluate the sedimentation stability of such mixtures. The experimental setup described here enables detection of vibration velocity only in the out-of-plane direction. Further investigations using a 3D Scanning Vibrometer which measures the complete displacement vector (out-of-plane as well as in-plane) have revealed that the velocity of propagation of transverse vibration components (shear waves) can be simultaneously acquired during the hydration. This is an interesting approach that allows for a more comprehensive assessment of the evolution of the material's elastic parameters including Young's modulus and Poisson's ratio.

Acknowledgement

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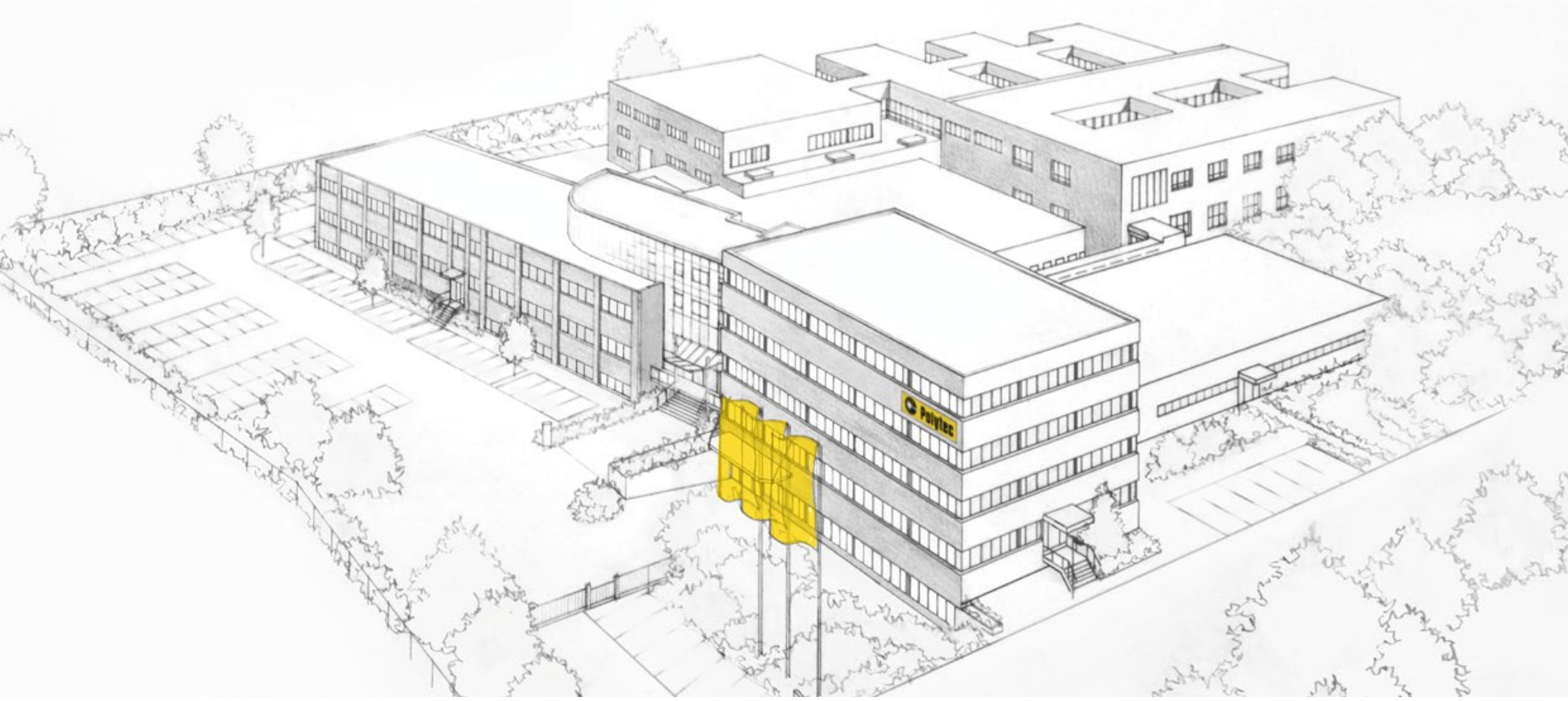

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