Characterization of laser-induced vibration on concrete surface toward highly efficient laser remote sensing

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Laser remote sensing (LRS) using irradiation of high-power laser pulses provides characteristic vibrations (CVs) which are accompanied by internal deterioration. While the principle of LRS is the same as that of the traditional hammering inspection, optimizing the irradiation parameters of laser pulses for vibrating samples is essential for effective LRS. In this study, the frequencies and magnitudes of CVs on a concrete specimen exhibiting a mock inside defect were evaluated by laser pulse irradiation and pendulum impact. When laser pulses were irradiated, the magnitude of CVs increased linearly with increasing laser pulse energy, and higher-order vibration was observed. On the other hand, an optimal spot size was indicated by the non-linear correlation between the fluence and the magnitude of CVs. To obtain an effective LRS, we propose that both high laser fluence and an optimized laser spot size are essential. © 2020 The Japan Society of Applied Physics

1. Introduction

The degradation of infrastructure (e.g., tunnels) can cause serious accidents. Periodic inspection to detect internal concrete defects using the hammering method is recognized as a major preventive measure to eliminate accidents. However, the hammering method does not provide remote sensing or a quantitative evaluation, and it is often time consuming. It is crucial to overcome these challenges to improve inspectors’ safety, reduce human errors, and successfully adapt the inspection methods to various types of infrastructure. Inspection methods for the detection of internal concrete defects employ ultrasound waves, electromagnetic waves, and acoustic sounds, which have been proposed to overcome the abovementioned challenges. However, considering the long track record of the hammering method, further efforts are required to enable the large-scale applicability of these methods.

A laser remote sensing (LRS) system for the inspection of internal concrete defects in infrastructure construction has been demonstrated. The measurement principle is based on human hammering and two laser systems are used. A high-energy laser pulse from an impact laser system irradiates an evaluation point such as a concrete surface, and vibrations are induced with hammering. Subsequently, the laser-induced vibration is detected with a laser Doppler vibrometer in a detection laser system as with the human ear. The detection range of the measurement frequency in LRS is 0.1 to 20 kHz, i.e., the audibility range, and the characteristic vibrations (CVs) resulting from its resonance frequencies are used to determine defects inside concrete. LRS was demonstrated with an inspection speed of 25 Hz for a concrete specimen 7 m ahead and quantitative digital data were provided. Studies with LRS were also applied for other inspections such as bolt fastening evaluation and medical diagnosis. Additionally, a sound source with laser-induced air breakdown was considered for application in analogical LRS schemes. Based on the facts above, LRS exhibits great potential as a next-generation inspection method for concrete infrastructure constructions.

The momentum toward the perpendicular direction to induce CVs is created via the ejection of concrete particles due to high inner pressure because of laser ablation. Laser ablation requires instantaneous heating by high-intensity laser pulses of over 0.1 GW cm⁻². Growth in the size of impact laser systems which provide high-energy nanosecond pulses is an unavoidable consequence of attempts to obtain a strong impact. A laser pulse width of nanosecond order is valuable in exciting the required frequency range for LRS during laser ablation. However, downsizing of the LRS system is especially important to expand the applied field. The footprint of an impact laser system is over 1 m² excluding additional systems such as power supplies, chillers and so on. Its size is adaptable in the case of truckloads for road tunnel inspection. However, a confined place would not be able to use the system because of its size. The limitation should be cleared by its downsizing. An effective generation of CVs on a concrete surface in LRS is conducive to detection accuracy enhancement and electricity usage reduction, and downsizing of the system is achieved as a result. As an application example of laser ablation, laser peening in material processing is well known. Laser peening results in a phenomenon that changes the stress field in metallic materials from tensile to compressive by the impulsive effect of laser-induced plasma from laser ablation. To optimize the laser peening process, the shock wave in metallic materials has been evaluated with different terms of laser intensity and ambient conditions, and laser wavelengths. A momentary magnitude of the shock wave within micro second result in laser ablation has been evaluated because generation of compressive stress in the laser peening technique was determined; however, persistent CVs which are detectable over the millisecond order have not been investigated in particular. CVs on a concrete surface occur by laser ablation through impact laser pulse irradiation. Precursiv
studies have reported a consistency between CVs induced by laser impact and modal vibrations calculated by the finite element method (FEM). The quantitative excitation forces that occur when laser pulses are irradiated to the surface of aluminum cubes have also been investigated using different pulse energies. In a previous demonstration, the spot size dependence of the magnitude of CVs on concrete surfaces was investigated. The magnitude of the CVs increased with decreasing spot size. Additionally, an induced vibration by laser pulse irradiation is an indirect process compared with hammering because of the zero mass of a photon. The laser pulse duration which is of the nanosecond order as defined by the FWHM of the pulse waveform corresponding to the contact time in hammer impact is over 1000 times shorter than that of hammer impact. Effects from different impact schemes should be investigated to optimize LRS.

2. Experimental sample

A concrete specimen was prepared as the experimental sample. Figure 1(a) shows the front view of the specimen. The size of the specimen was 300 mm on each side and the thickness was 100 mm. An internal defect made from polyurethane foam having a 5 mm thickness was set into a 10 mm depth from the front surface when the specimen was fabricated. The shape of the inside defect was determined by the hammering method, as shown in Fig. 1(a) by the solid line. An electromagnetic wave radar system (Structure Scan Mini XT, Geophysical Survey Systems, Inc., USA) was used to confirm the subsistence of the internal defect; the dotted line shown in Fig. 1(a) represents the measured line.

Figure 1(b) shows the evaluation result with the radar system in which the relative permittivity was set as 6.45 and the subsistence of the polyurethane foam whose relative permittivity was under 1.5 was confirmed to be approximately 10 mm deep from the specimen surface. The experimental sample close to the actual conditions was used. In particular, a suspended sample is frequently used in the evaluation of vibration characteristics but in this case, a sample simulating a defect inside was used to evaluate plate vibration not at the free end but at the fixed end.

The CV results in resonance frequencies were estimated prior to the experiments by FEM analysis (Fusion 360, Autodesk Inc., USA). Figure 2 shows the calculation results and the size of the circular plate model which was a simplified shape of the defect in the concrete specimen, i.e., 100 mm in diameter and 5 mm in thickness. In the FEM analysis, the assumed parameters of the concrete used were a density of 2300 kg m$^{-3}$, a longitudinal elastic modulus of 2.27 GPa, and a Poisson’s ratio of 0.2. The side surface of the model was completely fixed to simulate the vibration of the fixed end in the same conditions as the experimental sample. The calculated frequencies were (a) 1782 Hz, (b) 3417 Hz, (c) 5232 Hz, and (d) 5867 Hz. The first and second modes as shown in Figs. 2(a) and 2(b), respectively, were emphasized and the frequency until 10 000 Hz was analyzed in this study.

3. Details of pendulum impact and laser irradiation schemes

The indirect scheme with laser impact should be compared to a direct impact scheme. An impact hammer is commonly used for hammering inspection. However, the hammering force does not provide a constant impact force because of the taping by inspectors. An impact test using a pendulum was performed to quantify the impact energy in a condition close to that in hammering inspection. A steel ball of a diameter of 25 mm and a weight of 64.8 g was suspended by a string of a length of 80 mm. Figure 3 shows the experimental setup of the pendulum impact test. The center of the concrete specimen was impacted with the stringed steel ball and the impacted energy was defined with the potential energy of the rising steel ball. The time of impact $T_c$ and the maximum excitation frequency $f_c$ were estimated using Eqs. (1) and (2), respectively, as shown below:

$$f_c = \frac{2c}{\pi} T_c$$

$$c = \frac{\sqrt{2\pi f}}{2\pi}$$
where $D$ is the diameter of the steel ball. The time of impact $T_c$ was $108 \, \mu s$ for a 25 mm diameter ball. The maximum excitation frequency $f_c$ was 11 600 Hz based on Eq. (2), which matched the analysis range in this study. The detection laser was irradiated on the concrete specimen and the position was lateral to approximately 15 mm of the impact point by the steel ball to avoid an overlap between the detection laser and steel ball. The detection signal was acquired with a multifunction measurement system (RIONOTE SA-A1, RION Co. Ltd., Japan) and the time waveform was analyzed.

Figure 4 shows the experimental layout of the impact test by pulse laser irradiation. A Nd:YAG laser (LPY742-100, Litron Laser Ltd., UK) was used as the impact laser. The wavelength was 1064 nm and the pulse width defined with the FWHM was 14 ns, as shown in Fig. 5. The pulse energy of the impact laser was adjusted by the amount of transmitted light of the polarizing optical element, a half-wave plate, and a polarizer. The impact laser pulse was focused on the center of the concrete specimen with a lens of a focus length of 229 mm. The spot size focused on the concrete specimen was adjusted by moving the lens along the optical line and a defocused spot size — i.e., an expanded irradiation spot size — was obtained by moving the lens to the concrete specimen. Figure 6 shows the variations in the irradiation laser profiles and the spot sizes as denoted with the symbol $d$. The spot size $d$ was defined as the average of the diameters in the horizontal and vertical directions determined by the $1/e^2$ value of Gaussian fittings. In this study, eight types of spot sizes were used and the range was 0.554 mm to 2.52 mm. The detection laser was irradiated on the concrete specimen and the position was lateral to approximately 10 mm from the irradiation position of the impact laser pulse to avoid effects from the ablation plasma and/or plume to the detection laser. The detection signal was acquired with the multifunction measurement system, similar to the scheme in the pendulum impact test.

4. Experimental results and discussion

4.1. Influence of time domain and application to analysis in LRS

The difference in impact time between laser impact and pendulum impact should be investigated to determine the influence of the time domain. Additionally, the duration of the induced vibration is important in signal analysis to obtain the state of the concrete. Basically, the vibration signal was analyzed by FFT. In the FFT analysis, the time information was averaged and the short-time Fourier transform provided poor frequency resolutions in the uncertainty principle. If a direct analysis of the time waveform of the induced vibration was performed, Hilbert transformation would be effective in obtaining its envelope curve and the delay time would be useful to analysis. However, the complex time waveform including each vibration mode could not be analyzed simply. Therefore, it was essential to consider other analysis techniques.

The wavelet transform approach is an effective analysis technique for vibration frequency with time information. Figure 7 shows the binarization images of continuous wavelet transform analysis with a Mexican hat as the mother wavelet at different impact energies using (a) a pendulum and (b) laser pulse irradiation, and the threshold level was 75%. The vertical axis in Fig. 7 is an anomalistic scale determined by the mother wavelet and the scaling is inversely proportional. The durations of the induced vibration centered on 2000 Hz as the fundamental CVs were constant at approximately 40 ms regardless of the impact energy. Meanwhile, the durations of the induced vibration by laser irradiation were different based on the pulse energies of the irradiation laser, as shown in Fig. 7(b). The spot size of the impact laser pulse was 0.554 mm, which was the best focus. The duration increased with the pulse energy from 20 ms to 60 ms in this experiment. Similarly, the duration of the high-order CV which could be detected only in laser impact around 6000 Hz as shown in Fig. 7(b) peaked out by 40 ms. A variation in the duration for the induced vibration by the impact pulse energy is undesirable for detecting the onset of defects inside the

![Fig. 3. (Color online) Experimental setup of pendulum impact test.](image)

![Fig. 4. (Color online) Experimental layout of impact test by pulse laser irradiation.](image)

![Fig. 5. Waveform of impact laser pulse; the pulse width was defined by the FWHM.](image)
concrete with the delay time. Thus, analysis by the time waveform appears difficult.

The obtained durations of the induced vibration were configured with various vibration waves such as surface waves and reflected waves. Thus, the clipped duration of approximately 40 ms was decided by the onset of the internal defect and the concrete specimen itself—i.e. it would have been determined by the mechanical breaking strength, the mechanical parameter and the broad configuration. The short duration of the induced vibration with a low laser pulse energy implies an experimental result with a weak effect of the reflected wave because of the injection of a bare impact energy and because the phenomenon was provided only by laser ablation in this experiment. This implies an advantage of laser irradiation as an impact scheme and the signal variation would provide an option in analysis techniques by adjusting the irradiation energy of the laser pulse.

4.2. Variation of frequencies and magnitudes of the CVs at different impact energies

Figure 8 shows the variations in the (a) time waveforms and their corresponding (b) frequency spectra of induced vibrations on a concrete surface with different pendulum impact energies. The time waveforms shown in Fig. 8(a) were measurements triggered by the internal trigger of the multifunction measurement system. Because the time resolution of the multifunction measurement system was 19.5 μs, the impact time was approximately 0 s in this analyzed time range. The analyzed time range in this study was 0 to 100 ms based on a previous demonstration of LRS; this implies that the analyzed result included various vibration waves such as surface waves and reflected waves. The maximum amplitudes in the time waveform increased with the impact energy, and magnitude saturation was observed when impact energy was high. The frequency spectra as shown in Fig. 8(b) were analyzed with the time waveforms shown in Fig. 8(a) by FFT with a rectangular time-window function. A peak result in CV appeared at ~2000 Hz and the frequency was close to the estimated results by the FEM, as shown in Fig. 2(a). In this study, CVs of ~2000 Hz were defined as fundamental CVs.

Figure 9 shows the impact energy dependences of the magnitudes of the fundamental CV. Each plot of spectral powers and frequencies in Fig. 9 indicates the maximum value. According to Fig. 8, the magnitudes of the fundamental CV increased with increasing impact energy. Meanwhile, the frequencies of the fundamental CV were constant regardless of the impact energy.

Fig. 6. (Color online) Laser beam profile at each irradiation term; the diameter was defined as the 1/e² intensity of its Gaussian fittings.

Fig. 7. Variation of binarized continuous wavelet transforms by (a) pendulum impact and (b) laser pulse irradiation.
Meanwhile, for an impact by laser irradiation, the tendency was not the same as that by a pendulum impact. Figure 10 shows the variations in the (a) time waveforms and (b) their corresponding frequency spectra of the induced vibration on a concrete surface with different pulse energies of the impact laser system. The spot size of the impact laser pulse was 0.554 mm, which was the best focus. The time waveforms shown in Fig. 10(a) were measurements triggered by an external signal from a digital delay/pulse generator (DG645, Stanford Research Systems, USA). The digital pulse generator was used as a master clock and synchronized with a Q-switch signal in the impact laser system, and the laser pulse was irradiated at 1.2 ms, as shown in Fig. 10(a). The maximum amplitudes in the time waveforms increased with the impact energy; however, no saturation in the magnitude appeared in high impact energies. The frequency spectra as shown in Fig. 10(b) were analyzed with the time waveforms, shown in Fig. 10(a), by FFT with a rectangular time-window function. A fundamental CV appeared at $\sim 2000$ Hz as in the pendulum test. Fine peaks appeared at $\sim 3000$ Hz and 6000 Hz. The peak around 6000 Hz was defined as the maximum peak among the fine peaks and named a high-order CV, and it appeared only when laser irradiation was used. The pulse width of the impact laser pulse corresponded to the duration of impact and the maximum excitation frequency was 89.3 MHz as calculated using Eqs. (1) and (2) with a pulse width of 14 ns. In this experimental result, however, no typical peaks over 7000 Hz appeared. The FEM analysis, as shown in Fig. 2, provided a prediction of the resonance frequencies. Since the central part of the defect was excited in this experimental scheme, Figs. 2(b) and 2(c) were difficult to excite because of the shape of the vibration modes. The peak of 6000 Hz implies the vibration shape in Fig. 2(d) was a higher-order CV. The maximum amplitude of the time waveform and the maximum spectral power induced by the laser irradiation were only a tenth of those by pendulum impact despite exhibiting input energies 100 times as high. The impact energy could be transformed directly to kinetic energy for the CVs when the pendulum and hammer were impacting. However, for impacting with laser irradiation, complex processes for energy conversion occurred, thus resulting in kinetic energy for the CVs. The energy of the impact laser pulse was absorbed by the concrete; subsequently, the temperature was increased exponentially because of an optical–electric process including photoionization, multiphoton absorption, and electron avalanche. Finally, a plume and shock wave resulted in the generation of laser plasma and kinetic energy for the CVs was gained simultaneously with the generation of a loud sound and material heating. Therefore, the detection signal was smaller than that by pendulum impact.

Figure 11 shows the impact energy dependences of the (a) time waveforms and (b) their corresponding frequency spectra of CVs on a concrete surface with laser irradiation. The fundamental CV as shown by circle plots in Fig. 11 increased linearly with the pulse energy of the impact laser without signal saturation, and the frequency was constant with the pulse energy. Meanwhile, the high-order CV as shown by the square plots in Fig. 11 increased with the pulse laser energy in the unsaturated signal of the fundamental CV. The tendency of generation of the signal of the high-order CV was a critical difference as compared to pendulum impact and the peculiar excitation of CVs would be generated by the extremely short impact duration of the nanosecond-order laser pulse. The frequency was slightly varied because a proportion of the triplet peaks at $\sim 6000$ Hz as shown in Fig. 10(b) were not constant. As identified above, analysis with a combination of fundamental and high-order CVs in the

![Fig. 8. Variations in (a) time waveforms and their (b) corresponding frequency spectra of induced vibration by pendulum impact.](image-url)

![Fig. 9. (Color online) Impact energy dependences of the magnitudes of the fundamental CV.](image-url)
frequency spectra for vibration induced by laser irradiation would be predictably effective for determining the onset of defects inside concrete in terms of laser irradiation.

4.3. Fluence dependence of magnitudes of CVs induced by laser ablation

The pulse energy of the impact laser is an important parameter, as discussed in Sect. 4.1; however, the spot size and fluence, i.e., the laser energy density on the spot size, are essential as well. The amount of ablation plume is affected by the spot size of the laser pulse; therefore, the magnitude of the induced vibration would be affected as well.

Figure 12 shows the laser fluence dependence of the spectral power in the laser-induced fundamental CV [Fig. 12(a)] and high-order CV [Fig. 12(b)] at different laser spot sizes. The spectral power was defined as that of the evaluation, as described in Sect. 4.1. A plot with 72 different combinations between eight types of spot sizes as shown in Fig. 6 and nine types of energies (20, 35, 50, 75, 100, 150, 200, 240, and 270 mJ), and a range of fluences from 0.403 to 115 J cm⁻² is presented. The spectral power of the fundamental CV and high-order CV increased with the fluence. A high fluence of the impact laser could provide a high spectral power, i.e., a strong vibration, and the phenomenon indicates agreement with the general understanding that high fluence provides strong ablation. From a different angle, the adequate spot size provided an efficient generation of the peak of the fundamental CV and the high-order CV. The fittings in Figs. 12(a) and 12(b) are described for each spot size and the slope implies the efficiency of obtaining a strong vibration. For example, compared with 0.554 mm and 0.668 mm in Fig. 12(a), the large spot size provided a high rate of increase for the spectral power. The dashed lines in Fig. 12 are fittings by a power function described as \( y = mx^n \) and they indicate excellent agreement with the experimental results. Figures 13(a) and 13(b) show the relationship between the laser spot size dependences of the power of the fitting in Figs. 12(a) and 12(b) as described with fitting parameter \( n \). According to Figs. 13(a) and 13(b), an optimum value existed for the spot size and the tendencies of the optimization were not different between fundamental and high-order CVs. The scheme for the determination of the optimal spot size is not revealed; however, it is important to ensure that the area is as large as possible, i.e., exceeding the ablation threshold. The ablation thresholds of concrete and cement have been studied previously. 31 However, concrete is a complex chemical compound such that the feedstock, compounding ratio, and physical properties are different for every sample; therefore, the ablation threshold cannot be estimated easily. A detailed investigation would be essential to understand the relationship.

Fig. 10. Variations in (a) time waveforms and (b) their frequency spectra of induced vibration by laser pulse.

Fig. 11. (Color online) Impact energy dependences of the magnitudes of the fundamental and high-order CVs. Circle and square plots indicate the typical peaks at ~2000 Hz (fundamental CV) and 6000 Hz (high-order CV), respectively.
The contact area should be determined to evaluate the fluence of the impact energy in the pendulum test. Here, the contact area was estimated using Eq. (3) based on the Hertz contact theory:

\[
a = \sqrt{\frac{3\rho \left(1 - \nu_1^2\right)}{E_1}} \left[\frac{1}{R_1} + \frac{1}{R_2}\right]
\]

where \(a\) is the radius of the impact area, \(P\) is the load, \(\nu\) is Poisson’s ratio, \(E\) is the longitudinal elastic modulus, and \(R\) is the curvature radius. The parameters for concrete described as \(\nu_1\) and \(E_1\) were of the same value as in the FEM analysis, as shown in Fig. 2; furthermore, \(R_1\) was defined as infinity because of the flat surface. Meanwhile, the parameters for the steel ball were \(\nu_2\) and \(E_2\) of 0.27 and 152 GPa, respectively. The load \(P\) and curvature radius were used in the actual measured value of the mass and radius. The radius \(a\) was estimated to be approximately 0.0933 mm and used to indicate the impact fluence. Figure 14 shows the fluence and spot size dependences of the spectral powers for the (a) fundamental CV and (b) high-order CV. These spectral powers were estimated from the fitting parameters by a power function described as \(y = mx^n\), where \(m\) and \(n\) are shown in Fig. 12. The plots and solid line in Fig. 14(a) are the experimental results and fitting curve for pendulum impact as a function of the fluence converted from energy.

The order of impact fluence in the pendulum test was close to that by laser pulse irradiation. The excitation vibration of laser pulse irradiation with the best focus spot size \(d = 0.554\) mm (\(S = 2.41 \times 10^{-3}\) cm\(^2\)) and a fluence of \(13\) J cm\(^{-2}\) defined as the spectral power of the fundamental CV was approximately 97.3 times lower than that by pendulum impact, as shown in Fig. 14(a). However, the efficiency of the vibration excitation was improved by 6.8 times (i.e., 14.4 times lower than that by pendulum impact) with the optimization of the spot size to \(d = 1.38\) mm (\(S = 15.0 \times 10^{-3}\) cm\(^2\)), which yielded the highest efficiency, as shown in Fig. 13. The improvement by the optimization of the spot size was also efficient for high-order CVs, as shown in Fig. 14(b). The excitation vibration of the high-order CV by laser pulse irradiation with the best focus spot size \(d = 0.554\) mm (\(S = 2.41 \times 10^{-3}\) cm\(^2\)) at a fluence of \(13\) J cm\(^{-2}\) was improved by approximately 6.0 times with the optimization of the spot size. From these results, it is shown that the high fluence with an optimized spot size is comparable to pendulum excitation in terms of fundamental CV. Additionally, the vibration magnitude, i.e., spectral power, of the high-order CV induced by the optimized laser
irradiation was enhanced as indicated by the experimental data. Specifically, a laser spot size of approximately 1.5 mm was able to excite laser-induced CVs with high efficiency. The high pulse energy contributed to the high fluence, but the optimized spot size provided an LRS more efficient than that by increasing fluence as shown in Fig. 14. Additionally, the ratio of the high-order CV’s peak to the fundamental CV’s peak was constant at about 0.3 regardless of fluence. Therefore, LRS with analysis of high-order CV is particularly effective in terms of making the best use of the features of laser irradiation.

5. Conclusions

This study presents the first investigation to optimize LRS involving defects inside concrete at infrastructure constructions. The schematization of the effective ablation scheme by laser pulse irradiation was challenging because of concrete’s inhomogeneous properties owing to its complex chemical composition. Detailed investigation of the effects from feedstocks, the compounding ratio, and physical properties would be essential. However, the term suitable for practical use has been revealed herein.

We evaluated CVs induced on a concrete surface including internal defects by pendulum impact and pulse laser irradiation. Excitations of the fundamental and high-order CVs varied with the impact scheme. Pendulum impact induced only the fundamental CV. Meanwhile, laser irradiation induced the fundamental and high-order CVs simultaneously. The phenomenon would occur with an impact duration in the nanosecond order and combination analysis with both CVs to determine the onset of the internal defect would be effective for analyzing the impact by laser irradiation. The decay time of the induced vibration by laser ablation indicated typical findings. The increased decay time with increasing irradiation energy of the impact laser pulse would complicate the analysis of the onset of internal defects. To induce CVs efficiently, a high fluence of the impact laser pulse was essential. Additionally, the spot size of the impact laser pulse determined the excitation efficiency of the CVs, and the best focus was not an absolute term. Therefore, a high fluence provided with an adequate spot size that could ensure the ablation area on concrete and a high energy should be considered for optimization. From the experimental results, the high fluence with an optimized spot size was comparable to that in the pendulum excitation. This optimization scheme for high-efficiency laser impact will contribute to the downsizing of the LRS system.

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