様 式 C－１９、F－１９、Z－１９ （共通）

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研究課題名（和文）Two-beam probing laser-based system for remote inspection of unstable structures

研究課題名（英文）Institute for Laser Technology

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研究成果の概要（和文）：3年間の研究期間の間に、新しい手法のレーザーを用いた遠隔非破壊検査技術を開発および野外での実験を行った。新しい手法は、交通量の多い橋梁で生じる不規則な橋梁バウンドにより引き起こされるホモダイン受信法の信号強度の不安定さを極小化させるために2ビーム検出法を試験した。検査対象は高架橋鋼板接着床版の鋼板と接着剤の剥がれ（浮き）をターゲットとした。2ビーム検出法は従来の1ビーム検出法と比べて信号検出の観点から高い信頼性があることが分かった。しかし、日光、風、および音響のノイズ等からの影響があるために、今後、それらのプロテクション必要であると思われる。

研究成果の概要（英文）：A novel approach of laser-based remote non-destructive inspection of civil structures has been tested. The approach is based on using homodyne interferometry with two-beam probing for minimization of homodyne signal instability caused by irregular bouncing of inspected structure (like highway bridges). Two-beam probing method provides more reliable information of inspected structure conditions than conventional one-beam probing approach.
The system was designed, assembled and tested in laboratory. CO2 laser pulses with 4-Joule energy are used for initiation of vibration in inspected object. CW Nd:YVO4 laser with 0.5W output power is used as a source of two probing beams. Defects in the laboratory samples were recognized reliably. The system demonstrated significant benefit over conventional one-beam probing technique. A mobile prototype of the system was assembled and tested in the field conditions. The system demonstrated capability of real defect recognition in highway bridge.

研究分野： laser technology

キーワード： laser system　vibration measurement

１．研究開始当初の背景

The main goal of the project is the development of a laser-based system for reliable remote non-destructive inspection of various civil structures like tunnels, bridges, etc. The system is supposed to use laser impact for initiation of vibration in the inspected part of the structure and then detection of initiated vibration with the use of laser interferometer. Character of initiated vibration depends on presence/absence of possible flaws. This fact allows to locate even invisible inner defects.

The main reason of starting the project is non-successful attempt of laser-based inspection of unstable objects (highway bridges, actually) with the use of conventional homodyne interferometry. Instability of inspected object leads to fast movement of interference pattern in the detection path. As a result, reliable detection of initiated vibration is hardly possible. Heterodyne interferometry is free from this problem; however it requires using sophisticated and expensive equipment like frequency shifter and heterodyne signal demodulator.

２．研究の目的

The main purpose of the study was to find out and develop comparatively cheap approach of reliable laser-based remote inspection of unstable structures.

３．研究の方法

The key point of the development is implementation of new laser probing method for interferometry based on using two probing beams instead of single one. In this case, interference occurs between two signals formed from scattered radiation of the two probe beams. If the distance between the two probing points is much less than characteristic size of bouncing part of the bridge then these points will be moving almost synchronously. As a result, interference pattern will be much more stable and measurement of laser-initiated vibration will be much easier and cheaper.

In the present report, experimental tests of two-beam probing technology are described.

４．研究成果

(1) In Figures 1 and 2, laboratory installation is presented. Two probe beams are generated by CW Nd:YVO_4 laser Verdi-2, 532 nm wavelength. Output power used in the experiments did not exceed 500 mW. Source of impact beam is CO_2 laser generating pulses with 100 ns duration and 5 J energy. Output aperture of the impact laser is imaged to the target surface with scale M = -1. Resulting beam spot size on the target is 35 × 25 mm. Impact in thermal mode is realized providing real nondestructive inspection.

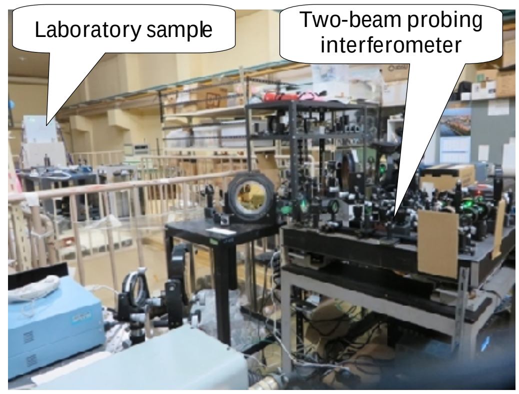


Fig. 1. Laboratory setup.

Fig.2 Impact laser unit.

The target is concrete sample with metal plate simulating bottom part of real highway bridge spans. The sample size is 450 × 450 × 150 mm. Distance from the interferometer is 7 m.

A specially designed algorithm of automatic scanning and real-time data processing has been implemented. To realize the algorithm, the system is equipped with combining and scanning mirrors shown in Figure 3. Combining mirror combines impact and probe beams: impact beam propagates through the mirror made of ZnSe, and probe beams are reflected by the mirror. As a result, after the combiner all beams propagate in one and the same direction.

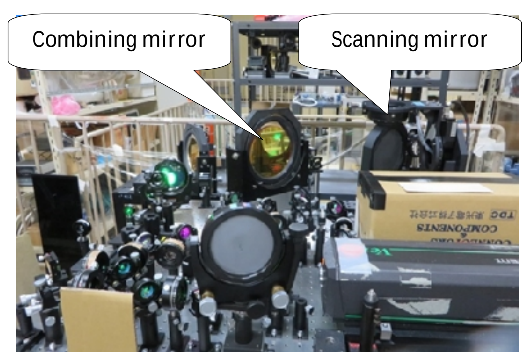
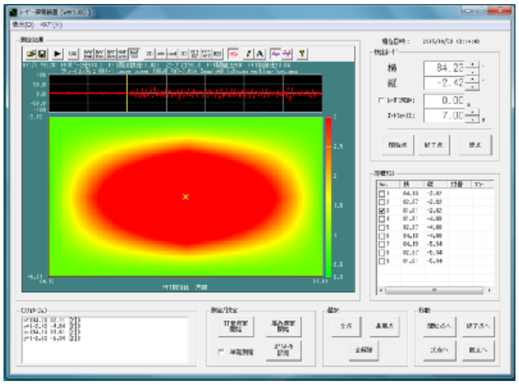
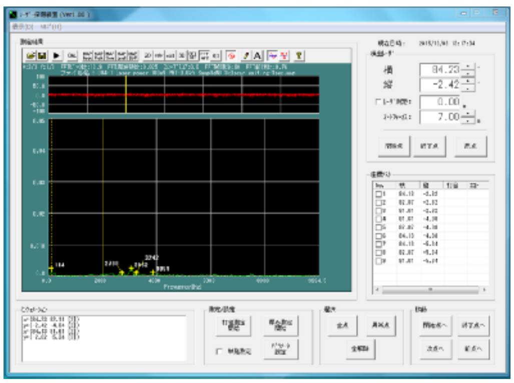


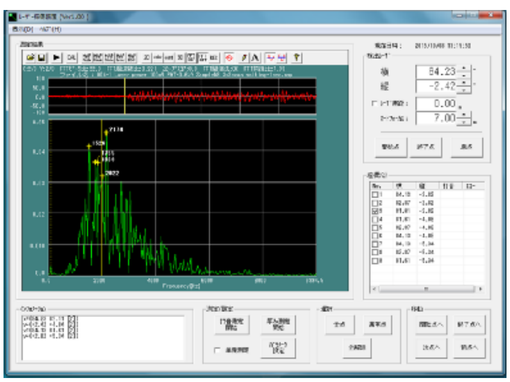
Fig.3 Combing and scanning mirrors.



a) 2D map of scanned area.



b) Spectrum of waveform before laser impact



c) Spectrum of waveform after laser impact

Fig.4 The main window of scanning/processing algorithm.

The scanning mirror reflects all three beams and controls their direction. The control may be taken both manually and automatically. Automatic control is performed by specially designed hardware and software (by Tecall Inc.).

In Figure 4, the main window of the control software is demonstrated. In Figure 4-a, two-dimensional map of inspected area is displayed. The map is real-time result of scanning the sample. Scanning area – 400 × 400 mm, scan points – 3 × 3, scan step – 200 mm. The sample center has inner defect. Its size is 300 × 300 mm. The central scanning point is located over defect area and the other 8 points are over no-defect area. In the resulting map, green field represent no-defect situation, red field – defect.

Defect recognition criterion is the presence of detectable standing Lamb wave initiated by laser impact. Spectra of waveform before (Figure 4-b) and after impact (Figure 4-c) are analyzed. Comparison between resulting spectral amplitudes gives information of the defect presence. In Figure 4-b the signal obtained in no-defect area is displayed. The signal waveform amplitude is near noise level and corresponding spectral amplitude is practically zero. In contrast, Figure 4-c presents waveform and its spectrum of vibration initiated in the defect area. In this case, vibration signal is clearly seen after moment of impact (vertical yellow line), and its spectrum has high spectral amplitude.

The control system allows to select inspected area (scan start and scan finish), scanning resolution (scan step number in two scanning directions), impact shot number (if data averaging is desired), waiting time after scanner movement (if necessary), trigger level. Single-shot mode is also available.

Two-dimensional maps can be saved along with waveforms obtained in each map nod for further processing.

(2) In the experiments, both two-beam probing and conventional one-beam probing techniques were tested. During scanning process, the inspected sample was kept still or it was shaken with simulating bridge spat vibration of 3 Hz with about 1-mm amplitude. The recorded waveforms are results of one-shot impact or averaging of three-shot impact. In each condition set, three records of initiated vibration were made.

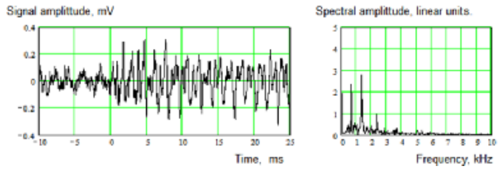
Figure 5 demonstrates examples of waveforms recorded in all conditions. Spectra next to the waveforms correspond to laser initiated signal (spectra of waveforms after impact).

Two-dimensional maps made in all sets of experimental conditions. In each sets of condition, three 2D maps were created including in total 3 points in defect area and 24 points in no-defect area. Figures 6 and 9 show the maps obtained under one-shot impact conditions.

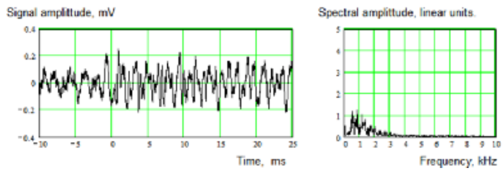
The experiments have proved that idea of two-beam probing is promising. In all conditions, recorded waveform is more stable and the signal of laser-initiated vibration looks much clearly when two-beam probing is used, especially it is noticed if the sample is shaken.

Ideal result of scanning is shown in Figure 4-a: central part is red, surrounding area is green. However, if the signal is unstable, sometimes data of real laser-initiated vibration may be lost and false recognition of no-defect area as defect situation may happen. In this case, central part of

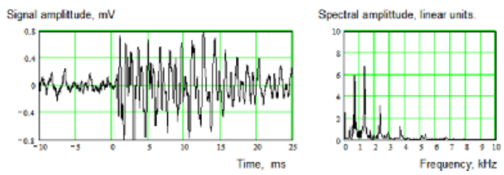
2D map will be green and edge part will be red.



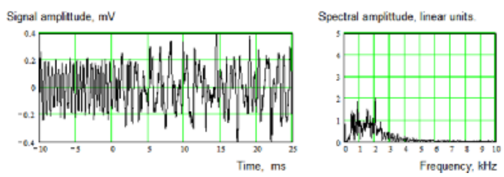
a) Two-beam probing, still sample, one-shot impact.



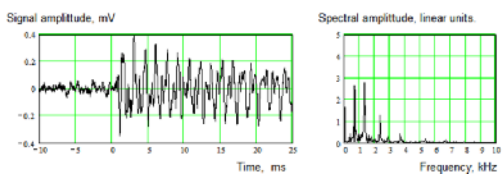
b) One-beam probing, still sample, one-shot impact.



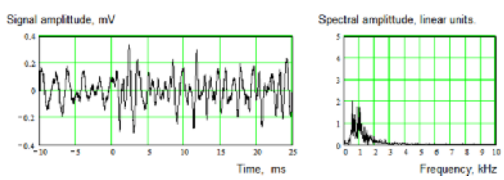
c) Two-beam probing, shaken sample, one-shot impact.



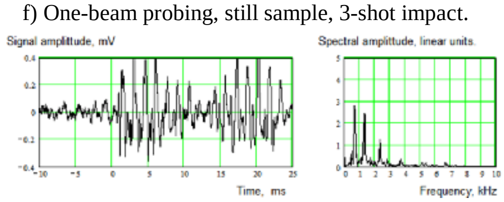
d) One-beam probing, shaken sample, one-shot impact.



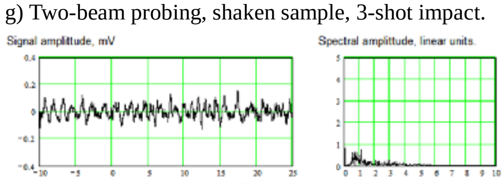
e) Two-beam probing, still sample, 3-shot impact.



f) One-beam probing, still sample, 3-shot impact.



g) Two-beam probing, shaken sample, 3-shot impact.



h) One-beam probing, shaken sample, 3-shot impact.

Fig. 5. Waveforms and spectra of laser-initiated vibration in the sample center. Impact – 0 ms.

Two-beam probing One-beam probing

1.
2.
3.

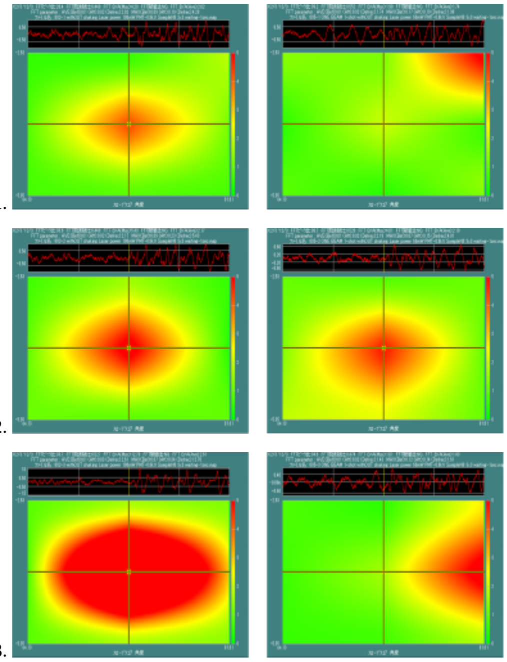


Fig.6. 2D maps. One-shot impact, still sample.

Two-beam probing One-beam probing

1.
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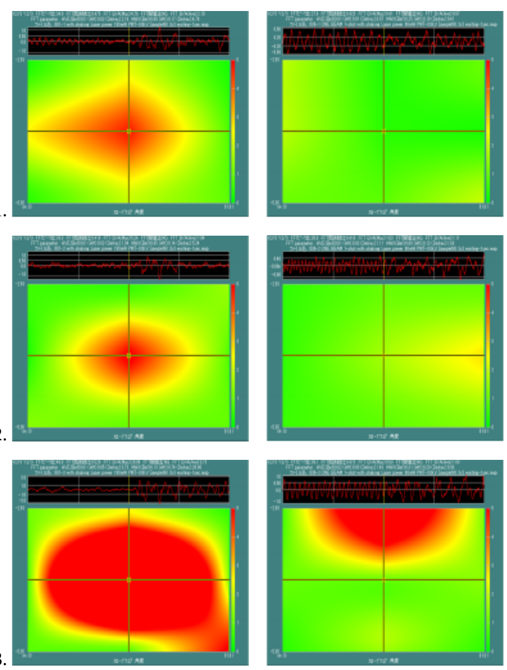

Fig.7. 2D maps. One-shot impact, shaken sample.

In the scanning results (Table 1), the use of two-beam probing provides much more reliable data. Defect situation is always recognized and fake recognition of no-defect as defect (red area in no-defect situation) happens seldom. In contrast, one-beam probing technique frequently misses the defect situation and frequently recognizes “defects” in no-defect area.

Table 1. Summary of scanning experiments

	Two-beam		One-beam	
Conditions	Defect	No-defect	Defect	No-defect
1-shot, still	3/3	24/24	1/3	22/24
1-shot, shaken	3/3	23/24	0/3	23/24
3-shot, still	3/3	24/24	2/3	20/24
3-shot, shaken	3/3	24/24	0/3	24/24
Total %	100	99	25	93

(3) After completing laboratory test, the system was prepared for field experiments under real highway bridge. To deliver the system to the field site, the interferometer and control equipment were loaded on a small truck and impact laser was loaded on a minivan.

Preliminary, the bridge bottom side was inspected by hammer for location of existing defects. After that, located defects were inspected by the laser-based system.

Basically, the system was capable to detect the located defects. Figure 8 demonstrated waveforms and spectra of vibration initiated in four different defect locations.

However, the system could not be used as it ws expected. The records shown in Figure 8 are just few good attempts of measurement. All the records were made with the use of two-beam probing. One-beam probing was just useless: signal was very unstable and laser-initiated vibration was not recognized as all. Probably, the system should be covered by tent providing protection against sunlight, wind and acoustic noise. Sunlight entering the detection path leads to saturation of photodetector. Wind was shaking the system carrier in horizontal direction. As a result, probes were bouncing not only vertically due to bridge span bouncing, but also horizontally due to system carrier movement. Two-beam probing idea is supposed to decrease signal instability caused by vertical movement of probes, across the inspected surface. In this case probe position on the inspected surface remains practically the same. However, horizontal movement of probes along the inspected surface leads to additional instability of speckle structure which cannot be minimized by using two-beam probing.

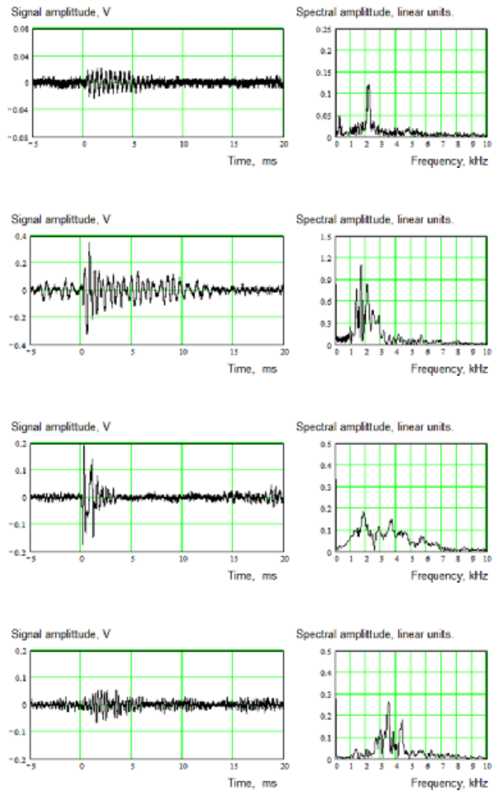

Fig.8. Waveforms and spectra of vibration initiated and detected by two-beam probing system.

Finally, the area under the bridge appeared to be very noisy, especially when trains were passing over the bridge. The acoustic noise affects the interferometry resulting in increasing of signal instability.

Because of so tough conditions in the field site, we could not make reliable 2D maps of located signals. However, in principle, the system was capable to initiate and detect vibration when the signal was comparatively stable. For the next experiments, we plan to use the system protection and hope to improve the system performance.

(4) Conclusions.

Mobile prototype of the laser-based inspection system has been assembled and tested in laboratory and field conditions

In laboratory, the two-beam probing system has demonstrated good performance with significant benefit over conventional one-beam probing technique

However, in field condition, the system performance was not satisfactory. Only few records could be made. Making 2D map was not possible. Probably, the system needs more careful protection against sunlight, wind and acoustic noise.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　0 件）

〔学会発表〕（計　1 件）
Oleg Kotyaev, Actual laser-based methods for remote inspection. 5-th US-Japan NDT Symposium, 2014-06-18, Maui, Hawaii, US

〔図書〕（計　0 件）

〔産業財産権〕
○出願状況（計　0 件）

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権利者：
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番号：
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発明者：
権利者：
種類：
番号：
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〔その他〕
ホームページ等

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