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Laser Speckle Correlation Method in Diagnostics of Bridge Span Vibrations

F.A. Gubarev[1,2], P.A. Elugachev[3], A.A. Bannikov[3], V.A. Nurzai[2], A.V. Mostovshchikov[1,3], Lin Li[4]

*[1]Tomsk Polytechnic University,
Lenin Ave., 30, Tomsk 634050, Russia*
*[2]Sevastopol State University,
Univesitetskaya str., 33, Sevastopol 299053, Russia*
*[3]Tomsk State University of Architecture and Building,
Solyanaya sq, 2, Tomsk 634003, Russia*
*[4]Liaoning Technical University,
Longwannan Ave., Huludao 125105, China*

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Abstract

Automobile bridge and overpasses are essential elements of transport infrastructure in every country. Rapid diagnostics and subsequent monitoring of critical bridge and overpass components' performance increases their service life. The aim of this study was to design a method and laser system for remote diagnostics of beam vibrations caused by dynamic loading and to apply them to a laboratory bridge model. The paper discusses a diagnostic method for bridge span vibrations based on laser-speckle correlation together with high-speed video recording. Using a laboratory model of a bridge, bearing structures under shock loading were studied by means of the proposed method. Relative surface displacements induced by different loading conditions were determined herein. The program for calculating correlation functions was optimized taking into account characteristics of the bridge span. In particular, surface displacements were analyzed with regard to the frame frequency and size of laser speckle patterns. Research technique was tested on the laboratory bridge model with beams made of different materials (steel, concrete, wood). For these beams, various shapes and amplitudes of displacements caused by shock loads are shown. Experiments demonstrate remote monitoring of bridge vibration under real shock loads caused by vehicle movement. This will be useful for further development of the proposed technique for bridge vibrations monitoring in real conditions.

Keywords: optical monitoring, bridge vibrations, laser speckle correlation, vibrational diagnostics, transport infrastructure

Адрес для переписки:
*Губарев Ф.А.
Томский политехнический университет,
пр-т Ленина, 30, г. Томск 634050, Россия
e-mail: gubarevfa@mail.ru*

Address for correspondence:
*Gubarev F.A.
Tomsk Polytechnic University,
Lenin Ave., 30, Tomsk 634050, Russia
e-mail: gubarevfa@mail.ru*

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Метод лазерной спекл-корреляции для диагностики колебаний пролётного строения моста

Ф.А. Губарев[1,2], П.А. Елугачев[3], А.А. Банников[3], В.А. Нурзай[2], А.В. Мостовщиков[1,3], Линь Ли[4]

[1]*Томский политехнический университет,*
пр-т Ленина, 30, г. Томск 634050, Россия

[2]*Севастопольский государственный университет,*
ул. Университетская, 33, г. Севастополь 299053, Россия

[3]*Томский государственный архитектурно-строительный университет,*
пл. Соляная, 2, г. Томск 634003, Россия

[4]*Ляонинский технический университет,*
пр-т Лонгваннан, г. Хулудао 125105, Китай

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Автомобильные мосты и путепроводы являются важными элементами транспортной инфраструктуры в любой стране. Оперативная диагностика с последующим мониторингом работоспособности критических элементов мостов и путепроводов увеличивает срок их службы. Целью данной работы являлась разработка метода и лазерной установки для дистанционной диагностики колебаний балки, вызванных динамической нагрузкой, и их применение на лабораторной модели моста. В статье рассматривается метод диагностики колебаний пролётного строения моста, основанный на корреляции лазерных спекл-изображений в сочетании со скоростной видеозаписью. С использованием лабораторной модели моста и предложенного метода исследуются несущие конструкции, испытывающие ударную нагрузку. При этом определяются относительные смещения поверхности, вызванные различными условиями нагружения. Программа для расчёта корреляционных функций оптимизирована с учётом характеристик пролётного строения моста. В частности, анализируются смещения поверхности с учётом частоты кадров и размера лазерных спеклов. Методика исследования апробирована на лабораторной модели моста с балками, изготовленными из различных материалов (сталь, бетон, дерево). Для этих балок показаны различные формы и амплитуды смещений, вызванных ударными нагрузками. Эксперименты демонстрируют возможности дистанционного мониторинга вибрации моста при реальных ударных нагрузках, вызванных движением транспортного средства. Полученные данные будут востребованы при использовании предлагаемого метода мониторинга вибрации моста в реальных условиях.

Ключевые слова: оптический мониторинг, вибрация моста, лазерная спекл-корреляция, вибрационная диагностика, транспортная инфраструктура

Адрес для переписки:
Губарев Ф.А.
Томский политехнический университет,
пр-т Ленина, 30, г. Томск 634050, Россия
e-mail: gubarevfa@mail.ru

Address for correspondence:
Gubarev F.A.
Tomsk Polytechnic University,
Lenin Ave., 30, Tomsk 634050, Russia
e-mail: gubarevfa@mail.ru

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1. Introduction

Road bridges and overpasses are the important elements of the transport infrastructure in any country [1–4]. It is especially relevant in areas with predominantly flat and marshy terrain penetrated by medium and minor watercourses also observed in the Tomsk region, Russia. The majority of bridges and overpasses in the Tomsk region have been built in 20th century. New bridges are built mostly in places, where previous constructions are failed or new transport nodes are constructed. Consequently, there is a need for prompt diagnosis followed by the health monitoring of critical elements of bridges or overpasses. The evidence from practice [3, 4] suggests that online monitoring increases the service life of bridges.

There are currently online monitoring systems installed directly on the bridge elements (primary on new bridges) and external monitoring systems. According to [5], these systems provide real-time observations of the bridge health and promptly respond to its changes. However, present health monitoring mostly utilizes contact methods [6–11]. Monitoring methods currently applied to bridges are associated with difficulties in the equipment installation in places appropriate for measurements and its expensive operation. These disadvantages hamper a wide implementation of on-line monitoring, which leads to decrease in the bridge safety and durability.

The advantage of optical diagnostic methods is contactless remote monitoring [12–17]. The diagnostic device can be placed tens of meters from the observation object. The coherent laser radiation provides a high measurement accuracy. A promising method based on laser radiation and videography is the use of laser speckles. According to [18–20], speckles are dark and light spots or marks that constitute a pattern. Speckle images are recorded by a digital camera, and the obtained pattern displacement is analyzed on a computer.

Artificial speckles produced by spraying pattern on the object surface [1, 21] are used in the field of measuring micro-displacement and deformation. Particularly, in paper [1] authors used digital speckle photography to investigate the bridge flexure model under static loading. Authors of paper [1] offer to coat the front surface of the bridge that is facing the camera with a special paint called retro-reflective paint, which contains imbedded minute glass beads. The size of glass bead is about 20–40 μm. When illuminated it reflects the light beam back to its source due to the index of refraction of the glass beads.

Authors of the paper [22] noted that they could identify about the natural frequency of spans using laser speckle imaging and parallel computing. The use of laser speckles does not require coating, i. e. allows us to select any monitoring area. Since laser speckles are formed in the space between the object of study and the camera lens, there is no need to focus the lens on the surface of the object of study. In addition, when working with laser speckles, a high-aperture lens is not required, unlike direct photographing of the surface. The use of a laser allows using the method at low lighting levels and does not require additional illumination. At the same time, a bright laser spot simplifies the adjustment of the monitoring system, especially if the camera is located at a significant distance from the object. It becomes possible to dynamically change the position of the control mark.

The aim of this work was to develop a method and laser facility for remote diagnostics of the beam vibrations induced by dynamic loading and their application to the laboratory bridge model. In this work, we use laser speckle correlation for a remote characterization of the beam deformation under dynamic loading. Experiments with the bridge model include shock loads on bearing structures made of different materials. Optical monitoring is applied in different areas of the beam associated with shock loading points.

2. Materials and methods

In our early research [23–26], we used the laser speckle correlation technique to investigate different processes. There were processes resulting in changes in physicochemical properties (the formation of blood clots or chemical transformations at high-temperature burning) [23, 24] and mechanical processes (membrane vibration at a sound reproduction) [25, 26]. In the latter case, laser speckles depended on the frequency and amplitude of the surface vibrations. We could expect that the same effect would be observed when beams of bridges or overpasses vibrate.

In order to implement the remote diagnostics of the span vibrations, we propose the compact imaging system based on a solid-state laser (illumination of the object to obtain laser speckle patterns in space between the span and digital camera), high-speed camera with objective lens (speckle image recording and transfer to a computer), image processing tool (speckle image processing and plotting), tripod and optomechanical devices (aiming the display system

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at the monitoring area) (see Figure 1). These studies used inexpensive commercial laser modules that can be integrated into a machine vision system with a relatively small increase in its cost.

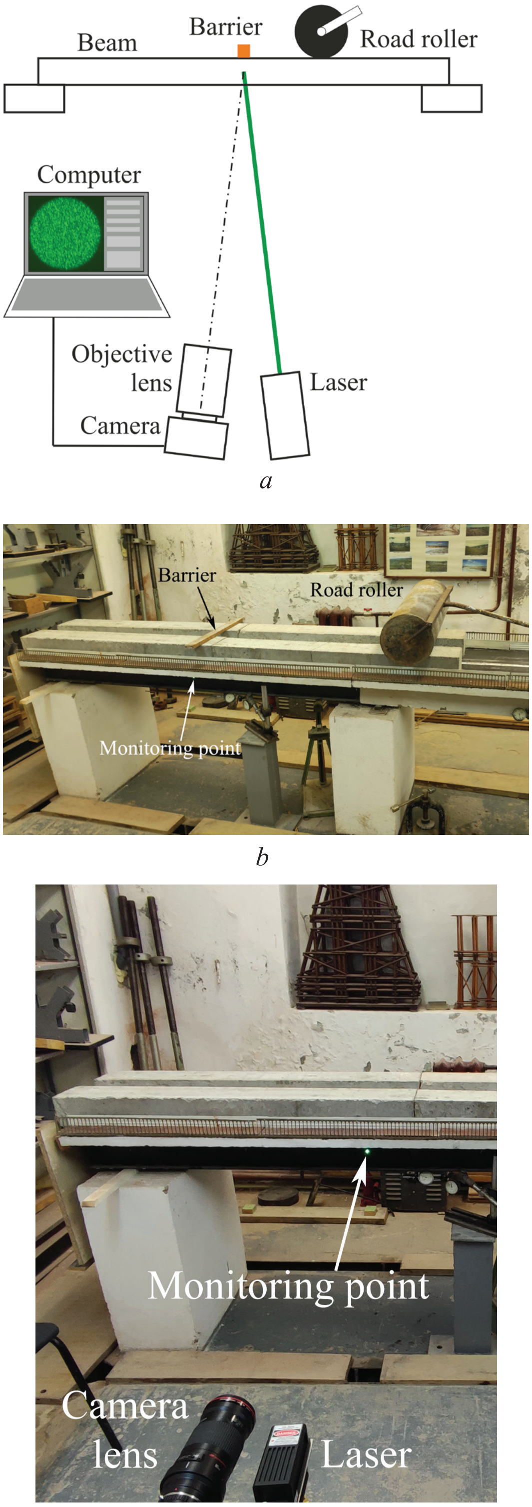


Figure 1 – Scheme of the experiment with dynamic loading by a roller (*a*); photographs of the test bench (*b*, *c*)

The laboratory bridge model was designed at the Department of Geological Engineering, Road Bridges and Facilities of Tomsk State University of Architecture and Building (Tomsk, Russia). Bridge spans with steel, concrete, and wooden beams were investigated. The steel and concrete spans consisted of two beams located at a distance of 0.3 m. The length of the beams was 1.9 m; the distance between the supports was 1.74 m. The two concrete beams had dimensions of 0.065×0.12×1.9 m^3. Two metal beams had an I-beam with dimensions of 0.05×0.12×1.9 m^3. The span with wooden beams consisted of five beams with dimensions of 0.03×0.12×1.9 m^3 with a distance between them of 0.09 m. A concrete plate with dimensions of 0.03×0.69×1.9 m^3 was placed on the beams. The bridge was additionally loaded with a static load in the form of concrete blocks measuring 1.205×0.155×0.103 m^3 and weighing 48 kg. A steel roller weighting 70 kg was used for the bridge loading. The roller was moved with and without a barrier on the beam, which simulated a dynamic load. The rolling speed was ≈1 m/s. The rail had a width of 50 mm and a thickness of 20 mm. When the roller hit the batten, an impact occurred. Laser monitoring was done in that place. The roller movement simulated shock loads applied to bearing elements made of different materials, over the beam. A schematic illustration of the experiment is presented in Figure 1.

The beam flexure was recorded by a mechanical dial indicator ICh-10 with a sensitivity of 0.01 mm and range of 10 mm, installed at a distance of 1.15 m from the beginning of the controlled beam. The operation of the mechanical indicator in the shock load mode was previously verified using the PHASE-1T vertical displacement measuring instrument, which has a basic permissible absolute measurement error of ±0.01 mm. The discrepancy between the readings of the instruments during simultaneous measurement of the deflection amplitude during impact did not exceed 5 %.

In addition to the described load, the point shock load was applied, as presented in Figure 2. It was carried out with a metal disk with a diameter of 0.25 m and a mass of 5 kg, freely falling from a height of 0.5 m. This experiment was conducted on a steel beam. The wooden bearing was on the left and the concrete bearing was on the right. The dynamic load was applied at points 1`–5` located at 0.2, 0.6, 1.03, 1.45 and 1.85 m distances to the left beam edge. Monitoring areas 1–5 located under points 1`–5`.

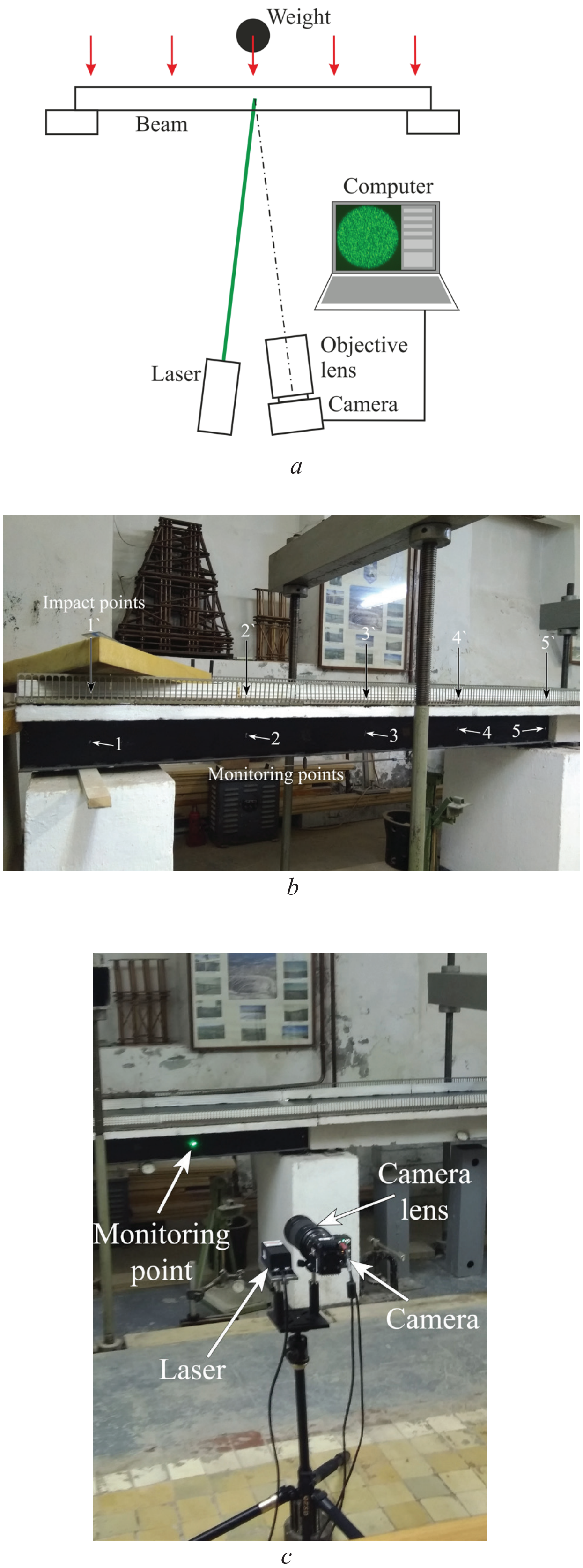


Figure 2 – Scheme of the experiment with dynamic loading by a free fall of steel disk (*a*); photographs of the laboratory bridge model (*b*, *c*)

Monitoring was carried out in the following order:

1) The imaging unit (camera and laser arranged on a tripod) was placed at a distance of 1.6 to 1.7 m to the observation object. This distance was limited by the laboratory space.

2) The optical system was adjusted such that the laser illuminated the monitoring point, and speckle images occupied 80–100 % of the imaging area in the window of the camera utility software.

3) The high-speed camera started recording ≈1 s prior to the bridge loading. After recording was completed, the images were sequentially transferred to a computer for storage and processing.

4) The next experiment was conducted according to item 3) with another bridge loading.

5) Recorded speckle images were digitally processed, and results were displayed graphically.

Digital laser speckle image correlation implies a search for a maximum correlation coefficient estimating displacements of image fragments or patterns. As it is illustrated in Figure 3, the point with coordinates x_1 and y_1 moves in a position with coordinates x_2 and y_2. If a subsequent image consists of the pattern g correlating with the initial pattern *f*, the speckle pattern moves from *f* to *g* position. The position of the maximum correlation coefficient is accepted as $g(x(C_{max}), y(C_{max}))$. In this work, we used the following normalized correlation coefficient for this purpose as more accurate according to our previous research [28]:

$$C = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}[f(x_i, y_j) - \overline{f}]\cdot[g(x_i', y_j') - \overline{g}]}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{m}[f(x_i, y_j) - \overline{f}]^2 \cdot \sum_{i=1}^{n}\sum_{j=1}^{m}[g(x_i', y_j') - \overline{g}]^2}}, \quad (1)$$

where $f(x_i, y_j)$ is the gray level of the area x_i, y_j in image 1; $\overline{f}$ is the average gray level of the area in image 1; $g(x_i', y_j')$ is the gray level in image 2; $\overline{g}$ is the average gray level in image 2.

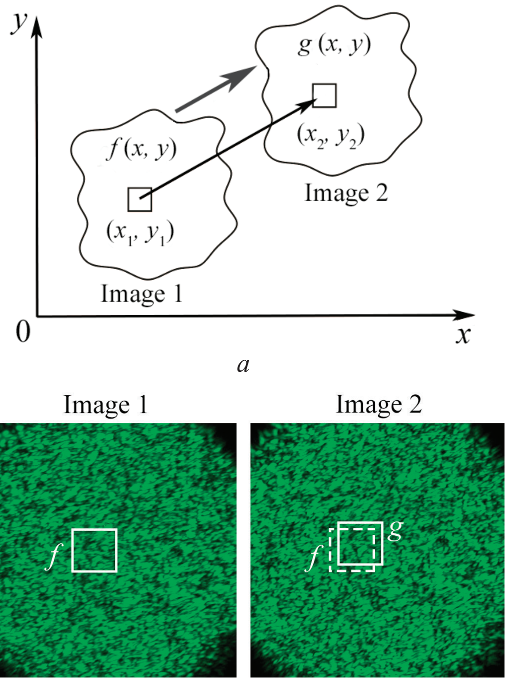
MATLAB package was used for speckle image processing and calculation of the correlation coefficient using (1). We used it in the previous works [14, 15] to study changes in the structure of materials. The program computed the maximum correlation coefficient C_{max} for every two adjacent speckle images (Image 1 – Image 2, Image 2 – Image 3 and so on). The displacement vector is determined by the difference between the coordinates of the initial position (x_0, y_0) of the pattern and the coordinates of the region with maximum correlation.

The maximum correlation coefficient value determines the value of the relative displacement of the pattern in pixels for the n^{th} image number in the sequence of recorded frames:

$$|R_n| = \sqrt{(x(C_{\max n}) - x_0)^2 + (y(C_{\max n}) - y_0)^2}. \quad (2)$$

The R_n value, taking into account the sign, is found as:

$$R_n = |R_n| \operatorname{sign}((x(C_{\max n}) - x_0) \cdot (y(C_{\max n}) - y_0)). \quad (3)$$

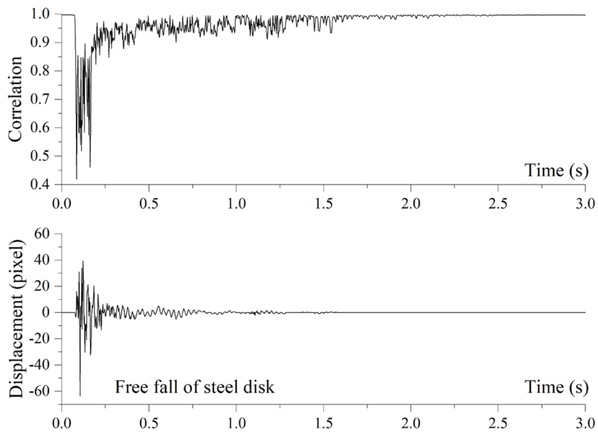


a

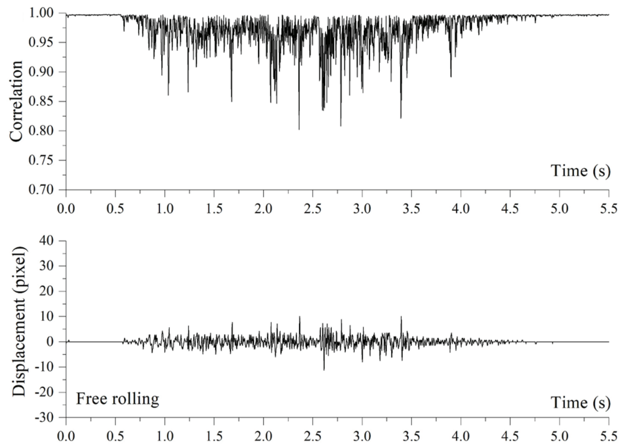
b

Figure 3 – Laser speckle displacement illustration: *a* – scheme; *b* – real laser speckles

In Figure 4, the correlation coefficient is presented relative to the pixel displacement in a series of experiments with the steel beam. The recording speed is 800 fps.



a



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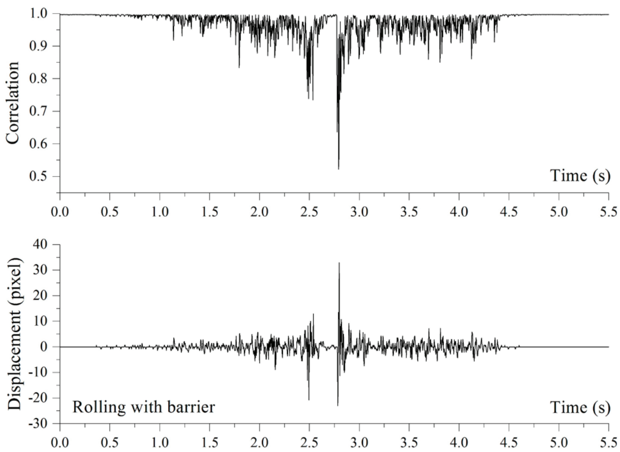


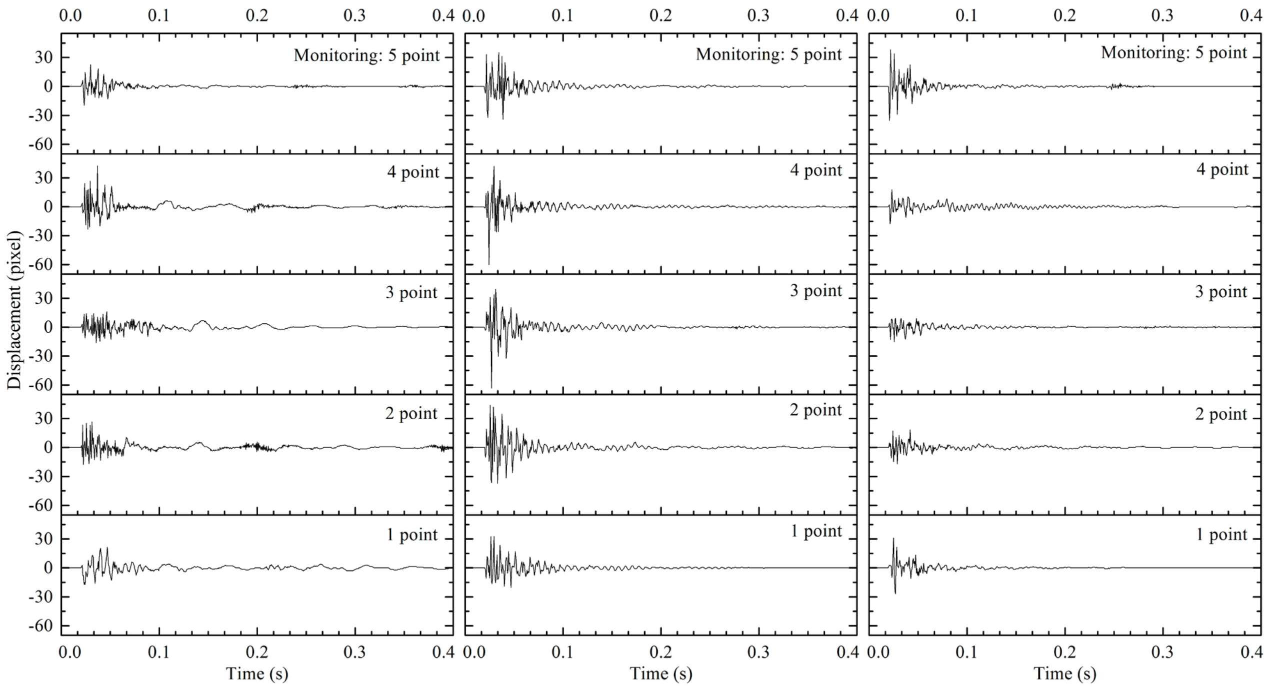
c

Figure 4 – Correlation coefficient vs. pixel displacement: *a* – free fall of steel disk; *b* – roller movement; *c* – roller over-barrier movement

3. Experimental results

3.1. Free fall of steel disk

In Figure 5, we can see the pixel displacement at different points, namely: point 1 (wooden bearing), point 3 (beam center), and point 5 (steel concrete bearing). There are also values of the displacement calculated for loads at points 3' and 5'. The recording speed is 800 fps. These data allow us to analyze the vibration behavior, depending on the loading position and decay time. The oscillations damping time is ≈40 ms for vibrations in the frequency range of 250 to 400 Hz, whereas in the range of 10 to 20 Hz, the damping time is 0.3 or 0.4 s. It is interesting to note the amplitude growth at the beam center and the difference in the vibration propagation at points 1' and 5'. This difference is conditioned by the shape and material of bearings. The steel concrete bearing is used at point 5 (minimum damping), while at point 1 the wooden bearing is used (significant damping).



a *b* *c*

Figure 5 – Pixel displacement recorded at points 1–5 at shock loads at different points: *a* – point 1'; *b* – point 3'; *c* – point 5'

3.2. Roller movement

Figure 6 contains plots of time and displacement relations for beams made of different materials subjected to the load induced by the over-barrier motion free rolling. The recording speed is 800 fps. The roller moves in the forward *F* and reverse *R* directions, i. e., to the left and to the right in Figure 1, respectively. These dependences allow estimating the movement time, structural vibrations, and also compare the impacts with each other. The diagrams of the free roller movement in both directions are almost similar for each material. However, slight differences are probably caused by either various moving velocity, or handle position of the roller. One can see that curves differ for various materials. For the wooden beam, we observe two peaks at the loading beginning and end; for the concrete beam, one peak occurs at the center, its amplitude is the highest among others. For the steel beam, several peaks are observed with one central peak, which exceeds the height of other peaks.

The bridge structure with the barrier is subjected to a higher impact than without the barrier that is confirmed by high peak values of the correlation coefficient and displacement. The diagrams describing the roller movement over the barrier (wooden batten at the beam center), demonstrate peaks matching the barrier entry and exit by the roller. As a rule, the vibrational amplitude during the barrier exit is higher than during entry. During the on-barrier time, the beam vibrations are the lowest. The vibrational amplitude, which matches the dynamic loading, is different for various materials.

The pixel displacement can be compared with the absolute displacement of the span structure. Due to the response time of the mechanical dial indicator, we suppose that the maximum pixel displacement of the speckle image corresponds to the maximum beam deflection measured by the indicator. In particular, the indicator response of 0.47 mm corresponds to 44 pixels of displacement (Figure 6*b*, *F* direction). At this stage, we can assume that 1 pixel displacement of the image matches the real surface displacement by ≈11 μm in current experimental conditions.

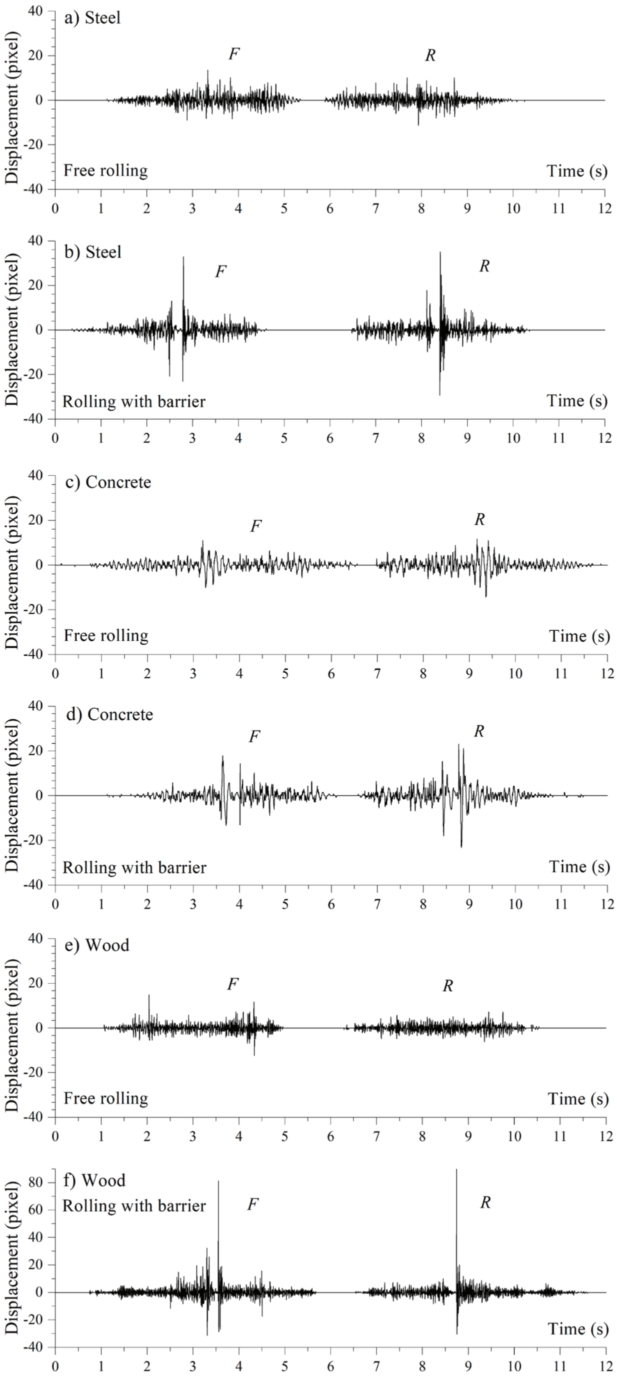


Figure 6 – Pixel displacement recorded during roller movement over different beams: *a*, *b* – steel beam; *c*, *d* – concrete beam; *e*, *f* – wooden beam

3.3. Parameter optimization of image recording and processing

It is important to detect the recording speed for practical applications of the proposed diagnostic method, design of a portable device for monitoring bridge vibrations, and choice of a digital camera with minimum requirements. Optimization of the frame frequency was carried out using the same datasets acquired at a frequency of 800 frames/s and then taking every second, fourth, eighth and sixteenth frames. Based on the analysis of only one process (shock load produced by a fall of steel disk), the time dependences are obtained for the pixel displacement and frame frequency. Results are presented in Figure 7. Based on the data obtained, recording at a frame rate of 800 frames/s gives a smaller amplitude compared to frame rates of 100–400 frames/s. In this case, the graph differs slightly from the graph obtained at a frame rate of 400 frames/s. Curves for frame rates of 400–800 frames/s contain a high-frequency component, which may be required for some tasks. At a frame rate of 200 frames/s, the main characteristic features of the process are recorded (the duration of vibration damping and the low-frequency component). Recording with a frame rate of 100 frames/s provides information about the onset of impact and intensity, while the decay time of the oscillations can only be estimated approximately. Recording with a frame rate of 50 frames/s or less is low informative.

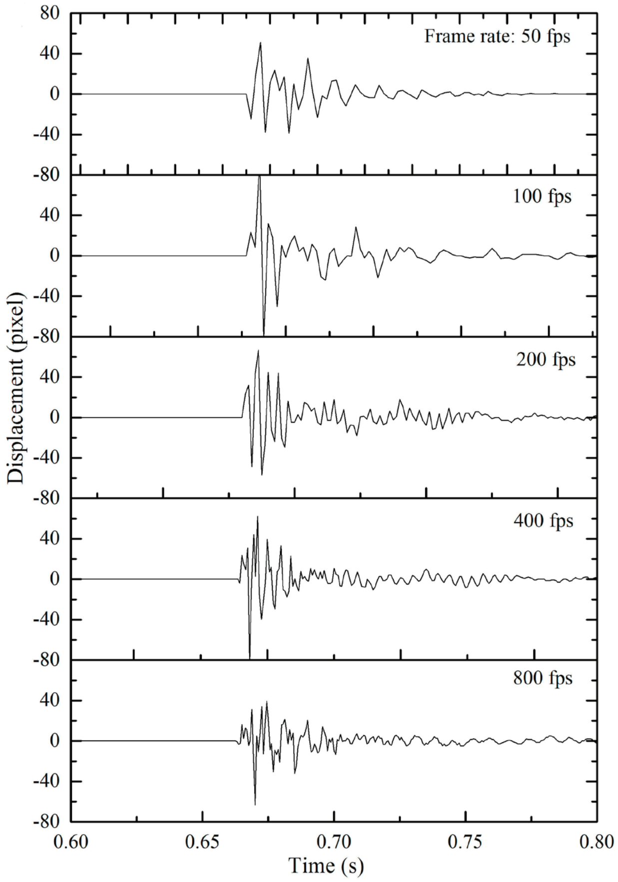


Figure 7 – Pixel displacement recorded at shock loads at different frame frequencies

The size of the computational domain (see speckle pattern in Figure 3) is an important parameter for the computational speed of the correlation coefficient. The size optimization of the speckle pattern has been conducted for the dynamic loading when moving the roller over the wooden beam with the barrier. Optimization is based on the same dataset obtained at 400 fps for the pattern sizes of 30×30, 50×50, 74×74, 150×150, 300×300, and 400×400 pixels. Results are presented in Figure 8.

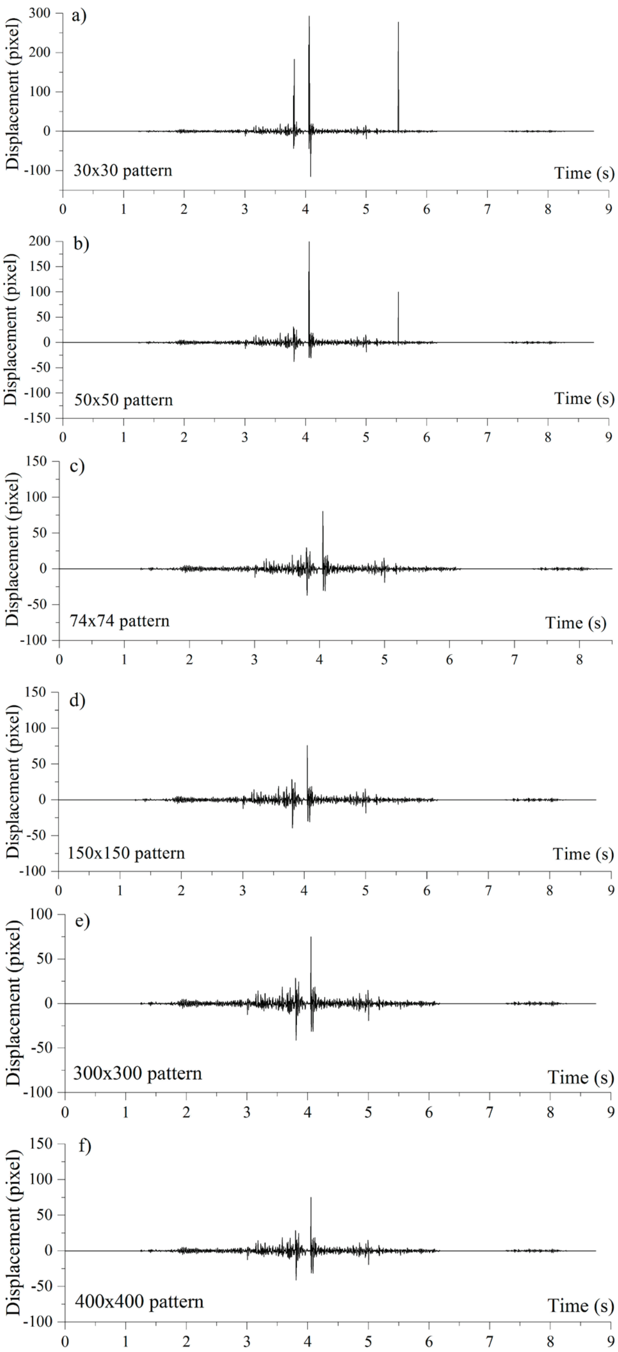


Figure 8 – Pixel displacement of speckle images with different pattern sizes: *a* – 30×30 pixels; *b* – 50×50 pixels; *c* – 74×74 pixels; *d* – 150×150 pixels; *e* – 300×300 pixels; *f* – 400×400 pixels

One can see that the pixel displacement is identical for pattern sizes from 74×74 to 300×300 pixels. At 400×400 pixels, the displacement amplitude slightly reduces, and the shape of curves is similar. Thus, the best size of the computational domain is ≈100×100 pixels. When the pattern size is 30×30 and 50×50 pixels, the peaks at the moment of impact are higher compared to other patterns (Figure 8). Therefore, the processing of images with the small computational domain demonstrates the higher sensitivity to the shock load. At the same time, the frequency spectrum is limited. This condition can be hardly used to analyze the vibration frequency of the span structure, although it can be used for the identification of influences.

Conclusion

In this work, the laser speckle correlation method was used to study the impact loading of load-bearing structures. Two loadings were considered: steel disk falling from a certain height and roller movement at a constant speed over the barrier placed at the span center. Based on the experimental data, the dependences were obtained for the correlation coefficient and relative surface displacement, such that to visualize the beam vibrations. Experimental results of shock loads at respective points helped to identify the behavior of the wave propagation. The promising development of remote non-destructive testing of the beam deformation under dynamic loading will allows identifying both the beam material (if necessary) and negative changes in its stress-strain state.

The computation program of correlation functions was optimized by two parameters: the size of the speckle pattern (computational domain of the frame) and sampling frequency (the equivalent of frame frequency). It was shown that the minimum size of the speckle pattern should be larger than 74×74 pixels, in order to analyze vibration processes. At a smaller size, the image processing speed and sensitivity to the shock load were higher. The study of the bridge beams made of different materials demonstrated specific characteristics for each material.

Ambient light reduces the visibility of the laser beam, resulting in changes in the intensity and contrast of the speckle pattern. This can be solved by using a more powerful laser. In natural light on a sunny day, the use of a 200 mW solid-state laser is sufficient when shooting from distances of about 20 m. The experiments carried out confirm that the influence of the angle of the laser beam relative to the surface with a slight deviation from the normal does not affect the efficiency and accuracy of measurements.

The advantage of the proposed technique based on laser speckle correlation, is a remote monitoring of the beam vibrations without the installation of equipment on the bridge. At the same time, the monitoring area can be changed rather quickly by using various directions of the laser beam. The compact optical part of the monitoring system can be accommodated on a camera tripod. Its power consumption does not exceed 1 kW, including a portable computer, high-speed camera, and laser facility. In field conditions, the monitoring system can be supplied from a diesel-driven generator.

Further research in this area involves designing a diagnostic complex for remote monitoring with laser speckle photography and digital image processing for studies of load-bearing structures, including field conditions. The pattern size of ~100×100 pixels, which is sufficient for calculations, does not impose high demands on the speed and resolution of the digital camera and allows choosing instruments that can be affordably deployed to many bridges. This also enables the implementation of streaming image processing for real-time bridge monitoring.

We suggest that future works will continue research into shock loads induced by the movement of rollers having different weight. This will model the different impact conditions and allow us to study the sensitivity of the proposed technique to the shock load and identification boundaries of certain influences and thus determine the best size of the computational domain for this purpose.

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