Measuring System to Monitor Deformation of Large Size Structure Members

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Abstract**—** About 250,000 bridges in use in the world require inspection and repair, monitoring and control of the condition of the structure. External conditions such as daily change in temperature, change in wind force and direction, rainfall, seismic shocks, and traffic load (number, weight, and speed of motor vehicle traffic on the bridge) are the most significant factors that influence the deformation of the bridge structure. The purpose of this article is to identify the most effective methods and measurement system for monitoring deformations of large structural elements. For the technical realization of this task it is necessary to develop a measuring system that will provide control of the deformation parameters of the bridge structures within the automated deformation monitoring system (ASDM). The use of a measuring system, which includes a laser beam scanner and analog-to-digital converters (ADCs), allows all measurements of deformations of objects of various lengths to digitize the ADCs "linear displacements - time - code", after which the converted information enters the computer. for further processing and storage, or for use in ASDM and others. And the use of ASDM, in turn, will allow you to quickly control the condition of the bridge structures, deflections resulting from the influence of external climatic influences, as well as intensive transport load. The developed methodology and the proposed system of measurement of deformations of large structures are proposed for the first time.

Keywords**—**laser, laser beam sweep unit, photodetector, analog-digital converter.

I. INTRODUCTION

Modern long length bridges can bear huge loads and strain partly because of their capacity to be slightly deformed under external conditions. The most considerable external factors that bring about the deformation of a bridge structure are the changes of external conditions such as daily air temperature, direct sunrays, wind force and direction, precipitation, wave motion, seismic shocks and traffic (intensity, weight and speed on a bridge). Even the most developed countries face problems in terms of bridges. For instance, in 2005 the Federal Highway Administration (FHWA) of the U.S. Department of Transportation established that about 15 % of 595000 American bridges do not meet design standards. In Europe about 10 % of bridge structures have defects and discrepancies between projects and bridges. All over the world about 250000 bridges in operation need inspection, repair, monitoring and control [1].

II. LITERATURE REVIEW

It is necessary to periodically monitor the bridge structure making the set of the geodetic measurement of its parameters to forecast the state of a bridge structure in order to be warned in advance about the tendencies of the changes of structure geometric parameters. However, in a critical situation the measurement does not enable us to get updated information and it does not contain enough information to calculate the real current dynamic characteristics of a structure to compare with design parameters. Therefore, at present, the task of topical interest is to develop a currently operating system that can collect, systematize, store, analyse, transform, display and disseminate the spatial coordinate data of a structure elements, which are monitored, during operation. In addition, the monitoring of such structures as bridges, having piers as high as some hundreds metres, has to be performed during construction. The monitoring of piers has to be performed before the project is implemented as the structure starts reacting to loads due to the changes of temperature, wind and increasing own weight per se

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during construction. It, in turn, can cause both the spatial deformation of the structure and the deviation from the project [1].

During the construction of bridges it is necessary to carry out periodical and permanent monitoring. However, as the construction process is coming to its completion, the permanent monitoring will grow in significance. The monitoring of a bridge state has to be fully performed during the construction as well as maintenance of bridge.

The use of the automated system of deformation monitoring (ASDM) for a bridge enables us to efficiently monitor the state of a bridge structure, its displacement and deflection that come into existence as a result of external natural and climatic factors as well as intensive traffic [1].

The indisputable advantages of the ASDM over the traditional methods of deformation monitoring are as follows:

- measuring of deformation values and their permanent comparison with permissible (design) deformation values in real time;
- possibility to monitor objects 24 hours, 365 days with specified resolution;
- high precision and uniformity of measuring, operator’s error elimination;
- remote control of the ASDM. Automatic data collection, the preliminary analysis of the information and sending it to any terminal using the Internet or other communication channels are carried out;
- the ASDM can be designed in such a way that, when critical values or dangerous tendencies (speeding up) of deformation processes are detected in an object, an alert with automatic notification of authorities is triggered using communication links to make an urgent decision, avoid accidents and save people.

The automated system of deformation monitoring allows us to measure non-stop the deformations (displacements) of object structure elements. Digital monitoring sensors help us detect object deformations if they are beyond standards. It guarantees pinpoint accuracy in real time using the appropriate specification and configuration of the ASDM. The results of measurement from various gauges provide information about the conditions of object operation and their impact on geometric stability and durability of objects. So, the ASDM enables us to analyse deformations and model the forecast of an object behaviour in general and its structural components in particular [2].

To control and forecast the state of a bridge structure with the ASDM, optical methods to measure deformation are widely spread. Due to various optical systems, practically all images, starting with medical papers on a cell level, the pictures of the surface of nuclear reactor fuel elements and ending with cartographic data and the measurements of the deformation of various length objects, have high precision and clearness. Then the images are digitized with the help of analog-digital converters (ADC) and enter a computer to be further processed and stored or used by the ASDM, an automatic control system to control a technological process etc. To convert measured information about object parameters into digital form, the analog-digital converters “analog – time – code”, “analog – frequency – code” and “analog – phase – code” are used. An analog-digital converter engineering approach to convert information came into existence in the 70s–80s of last century [3].

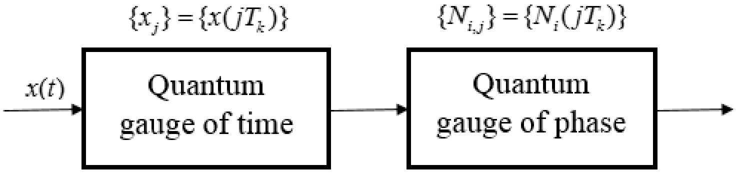
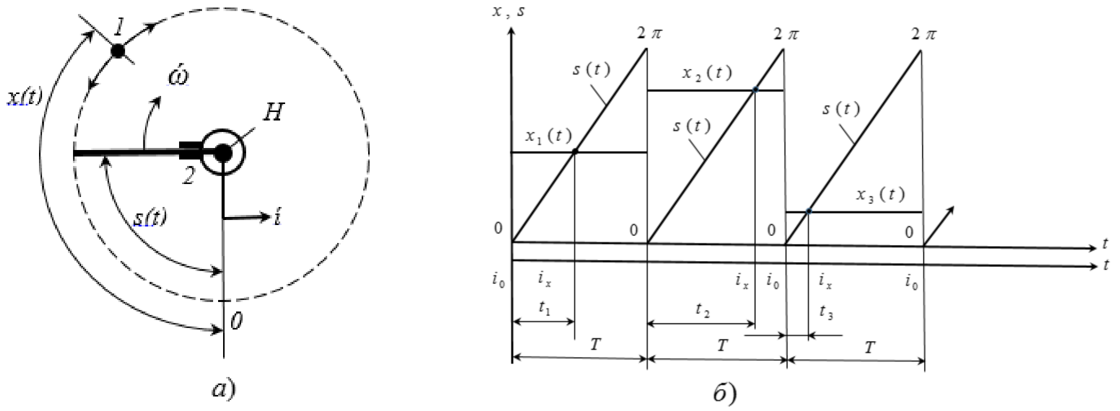


Fig. 1 Functional scheme of ADC

The ADC receives the input analog signal $x(t)$ that, having passed through a sampler, is converted into the sequence of samples $x(jT_k)$. A quantizer converts the sequence of samples into the sequence of codes $N_i(jT_k)$ where the index i corresponds to the i-th level.

At present the ADC continues developing and improving in terms of operation speed, noise immunity, precision and microminiaturization [4]. For example, in a device to measure deformation, a multielement photodetector, which is designed as a matrix, detects the quantity and direction of deformation. If a narrow-beam light pulse simultaneously comes to several photocells of a multielement photodetector, deformation distance and direction are calculated as arithmetical mean value of the quantity of all lighted photocells [5].

Geometric scanning systems, similar to that described in [6], can form the basis for the measurement of the deformation of long length objects.



a)

б)

Fig. 2 Geometric scanning system

In a geometric scanning system (Fig. 2, a), the parameter, which is scanned, is an angle x(t) that determines the location of object 1 on a circular trajectory. The scanned element 2, which is in the centre of a circle, is a prism or mirror. They are located on an engine shaft at an angle of 45o with a laser beam. During uniform rotation with angular velocity $\omega = const$ element 2 periodically meets zero sign 0 and object 1 at angles $s = 0$ and $s = x$. At the same time the zero control H of on-off action generates pulses i_0 and i_x that on a geometric or temporal scale correspond to instant angles s_0 and s_x. These pulses can be transmitted at distance or used at the spot to monitor and control [5].

The process of scanning in Fig. 2, b has a sawtooth function $s = \omega \cdot t$ over a period of $T = 2 \cdot \pi / \omega$ and current time $t = s / \omega$. The diagram shows three angular positions x_1, x_2 and x_3 that correspond to the points of time t_1, t_2 and t_3, the meeting of elements and the generating of pulses i_x. Time is calculated from the beginning of each cycle [5].

These systems are the basis to design some equipment that contain n sequentially allocated strain gauges, which are rigidly fixed on a structure in deformation; each of them has a semi-reflecting mirror, cross mark, light source, light receiver, focusing unit and scanning light unit that are located sequentially along an optical axis between a light receiver and semi-reflecting mirrors. At the same time, n light sources and n cross marks are also located along the optical axis of each gauge that is perpendicular to a main optical axis between a semi-reflecting mirror and a light source. In addition, the gauge has a detector and a switching unit whose input is linked to a light receiver and outputs are linked to a focusing unit, n light sources and a detector that contains a measuring circuit and a computing unit [7, 8].

III. AIM AND PROBLEM STATEMENT

The aim of this paper is to determine the most effective methods and a measuring system to monitor the deformation of large size structure elements. In order to technically perform this task, it is necessary to design a measuring system that guarantees the monitoring of bridge structure deformation parameters when using the ASDM.

IV. DESIGN OF MEASURING SYSTEM

As part of the ASDM, the measuring system of bridge structure deformation, which consists of a laser, optical collimator, unit of laser beam sweep, n photodetectors, switching unit, converter "linear displacements – time – code" and detector, is proposed. All n photodetectors are n sequentially located strain gauges that are horizontally positioned on supports at an equal distance from one another along a structure and rigidly fixed on the structure in deformation. They can be, for instance, electric poles to light a road on a bridge (Fig. 3) or special supports, which are in Fig. 4.

Fig. 3 Electric lighting of roadway on the bridge

Fig. 4 Special supports to fix strain gauges-photodetectors

The output of every n photodetector is connected to the inputs of a switching unit and its output – to the input of the converter "linear displacement – time – code", which output is connected with the input of a recorder; every consecutive photodetector, which is fixed to a pole, is located at a certain equal distance from one another vertically, and the first and n-th photodetectors, laser, optical collimator and a unit of laser beam sweep are located beyond the bounds of the structure in deformation.

The system operates as follows. To measure the deformation of a large size structure, n photodetectors 3_1, …, 3_n are used. They are n consecutively located strain gauges, which are fixed to supports 2_1, …, 2_n that are at a certain equal distance d from one another horizontally along structure 1 and rigidly fixed to the structure (Fig. 5). The first and *n*-th photodetectors are located beyond the bounds of the structure. In addition, laser 4, optical collimator 5 and a unit 6 of laser beam sweep 7 are located beyond the bounds of the structure. The gauge uses a laser that continuously radiates a beam of a certain wavelength. The optical collimator, which consists of a lens, which has the output of a laser beam in its focal plane, is located in series with the laser. Optical collimator 5 guarantees a parallel laser beam and due to practically zero divergence all the energy of a laser beam is focused on the sensitive surface of each photodetector, which is made of a special material that creates no obstacle for a laser beam.

The n photodetectors contain a photodiode or photoelectric multiplier. A sensitive surface and an optical filter, which let the beam of a certain wavelength pass, are positioned before a photoelectric multiplier. All the elements of a photodetector are in a hermetic container. The unit 6 of laser beam sweep, for example, is a motor which shaft houses a mirror or a prism having a mirror face, which are located at an angle of 45^{o} with a laser beam, or a rotary optical wedge due to which a laser beam sweeps in the vertical plane.

The optical signal, which sweeps, from a unit 6 of laser beam sweep sequentially passes the sensitive surface of every 3_1, …, 3_n photodetector of a certain length h (Fig. 5, Fig. 6).

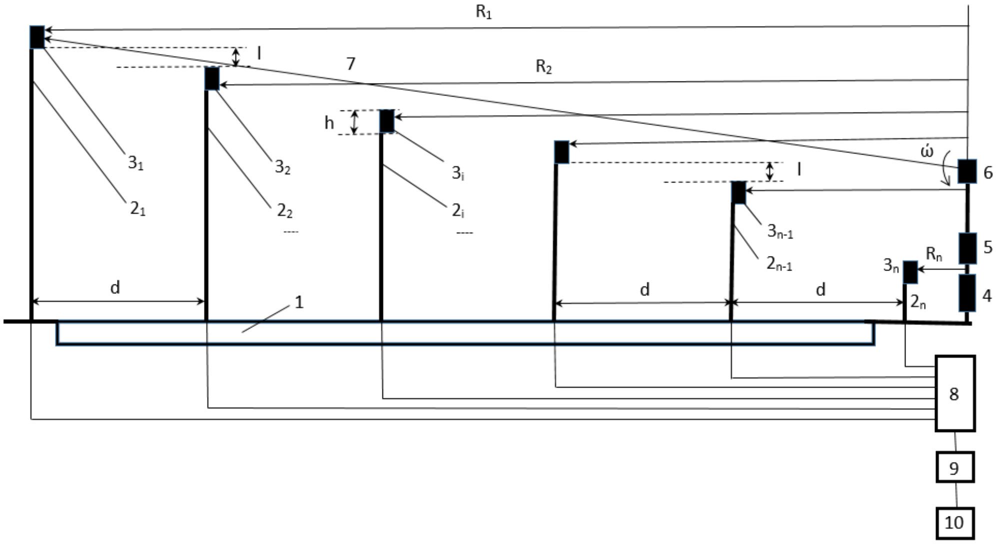


Fig. 5 General view of device and position of photodetectors on a structure without deformation

An electric signal from a photodiode or photoelectric multiplier goes to the electric signal amplifier of a photodetector and after amplification it goes to a switching unit 8. The time span of an electric pulse coming from the output of a photodetector is determined by the beam transmission rate along the sensitive surface of a photodetector. The rate will, in turn, be determined by both the angular velocity ώ of the motor of a sweep unit and the distance R between a sweep unit and a photodetector (Fig. 5, Fig. 6).

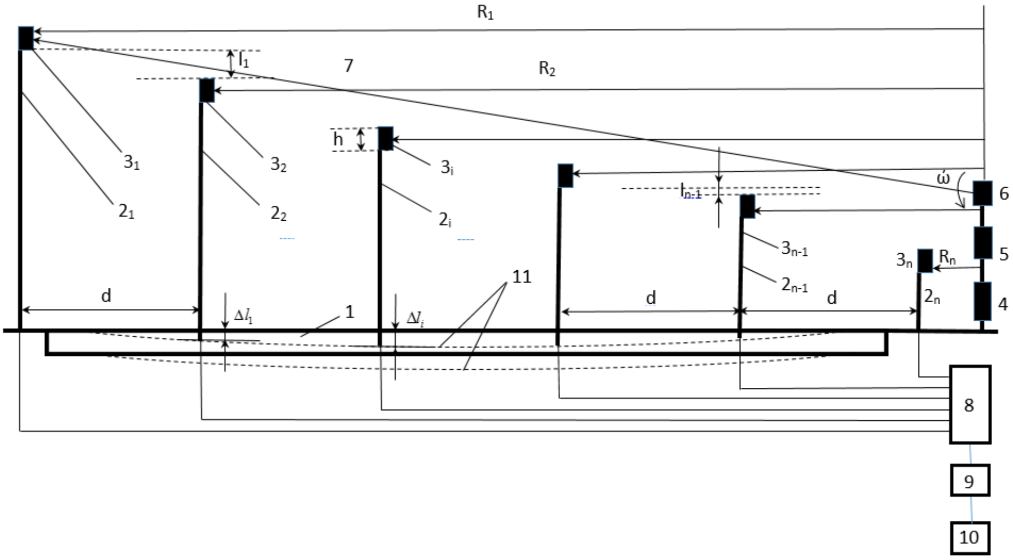


Fig. 6 General view of device and position of photodetectors on a structure with deformation

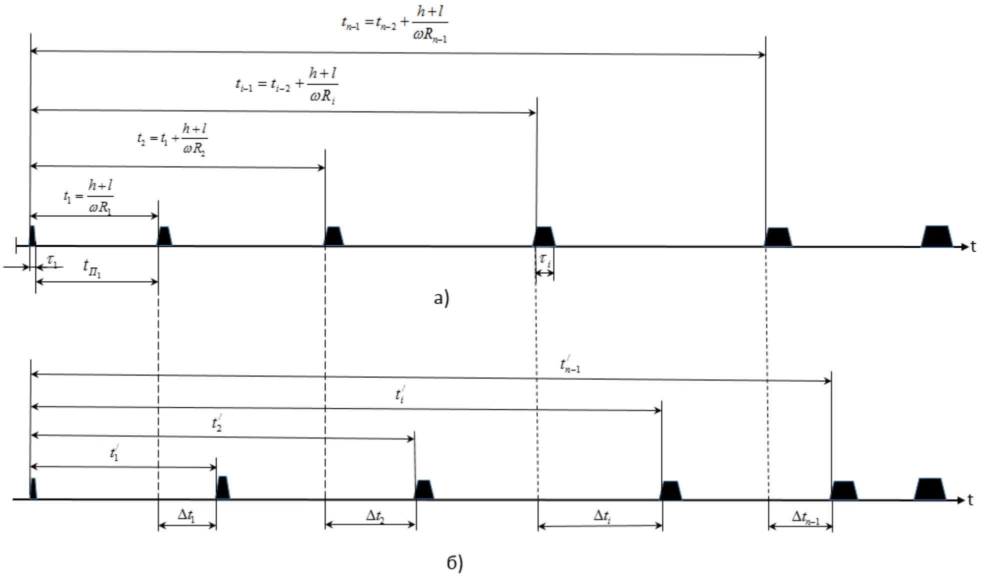


Fig. 7 Time chart of device operation without structure deformation (a) and with structure deformation (b)

So the time span of pulses from a photodetector will vary; it will be increasing when a photodetector is approaching a sweep unit (Fig. 7 a, b)

$$\tau_1 = \frac{h}{\omega R_1}, \tag{1}$$

where ώ = 2·π·f is the angular velocity of motor rotations; R1 is the distance between the sweep unit of a laser beam and the first photodetector.

Then for the i of the photodetector, the pulse time span will be

$$\tau_i = \frac{h}{\omega R_i}\,, \tag{2}$$

where i = 1…n.

The distance l between photodetectors is the same in the vertical plan (Fig. 5), the distance (pause) between electrical pulses will be increasing as photodetectors are approaching a sweep unit (Fig. 7, a).

$$t_{\Pi_i} = \frac{l}{\omega R_i}\,, \tag{3}$$

where is the distance between the electrical pulses of two photodetectors; *l* – the distance (pause) between photodetectors; *i* = 1…*n*-1.

As the first 31 photodetector is beyond the structure in deformation, the calculation of deformation Δl_i is made relative to the first photodetector (Fig. 7, a). So

$$\begin{gathered} t_1 = \tau_1 + t_{\Pi_1} = \frac{h+l}{\omega R_1}\,, \\ t_2 = t_1 + \frac{h+l}{\omega R_2}\,, \\ t_i = t_{i-1} + \frac{h+l}{\omega R_i}\,, \\ t_{n-1} = t_{n-2} + \frac{h+l}{\omega R_{n-1}}\,. \end{gathered} \tag{4}$$

If the structure is deformed (dotted line 11 in Fig. 6), the vertical distance between photodetectors will change from l_1 to l_{n-1} respectively (Fig. 6). So the time span of pulses will be similar to the structure before deformation (Fig. 5) but the time span between pulses and the period of pulse-passing time will change respectively and depend on Δl_i

$$\Delta l_i = l_i - l\,, \tag{5}$$

where Δl_i – deformation value; *i* = 1… *n*-1.

Analogous (4) calculation $t_1^{/}$, $t_2^{/}$, …, $t_i^{/}$, …, $t_{n-1}^{/}$ is made for a deformed structure too (Fig. 7, b).

Then

$$\frac{t_i}{t_i^{/}} = \frac{l}{l_i}\,, \tag{6}$$

therefore

$$l_i = \frac{l \cdot t_i^{/}}{t_i}\,. \tag{7}$$

Then, taking into consideration (5), equation (7) has a form

$$l+\Delta l_i=\frac{l\cdot t_i^/}{t_i}. \tag{8}$$

Therefore

$$\Delta l_i=\frac{l\cdot t_i^/-lt_i}{t_i}=\frac{l\cdot(t_i^/-t_i)}{t_i}, \tag{9}$$

but $\Delta t_i=t_i^/-t_i$ (Fig. 5, b).

So equation (9) has a form

$$\Delta l_i=\frac{l\cdot\Delta t_i}{t_i}. \tag{10}$$

Signals from photodetectors 3_1, …, 3_n through switching unit 8 go to converter 9 ADC “linear displacement – time – code”, then they go to recorder 10 after having been converted and calculated. The calculation of t_i and $t_i^/$ in equation (9) is made using either the traditional method, for instance, of the filling of the intervals between two rising edges of the pulses of two corresponding photodetectors with the pulses of a stable frequency clock generator or the nonius method using a shock-excited oscillator, which are in converter 9, and *l* is known beforehand.

CONCLUSION

The deformation measuring system can be used in the ASDM of bridge structures and other members of large size structures. It enables us to efficiently monitor their state, displacement and bend that come into existence as the result of external natural climatic impacts as well as intensive traffic.

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