Use of Mobile Measuring System for Bridge Monitoring

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ABSTRACT: Continuous monitoring of bridges provides information on the bridge condition and permits to forecast structural deterioration. This allows for prompt measures of repair and rehabilitation to be timely taken and ensures the reliable functioning of a given bridge. Monitoring was conducted with the aid of a mobile monitoring unit, the main advantages of which are its repeated utilization relative simplicity of installation and suitability for any period of the bridge’s life cycle. The system consists of displacement transducers and data loggers. As a result of the year-long monitoring it was found that the vertical displacements (40-50 mm) in the joint were only of seasonal character. Furthermore, unsatisfactory performance of the key joint was identified. It had manifested in discrete and delayed movements of up to a few hours as compared with the joints at the arch abutments. Replacement of the joints was fitted into the major repair schedule of 2006-2007.

In major cities operational environment the reliability of bridge network is always critical. Therefore it is necessary to have full and detailed information on every structure that helps us forecast changes in their operating conditions in time.

One of the methods of obtaining such information is the instrumental monitoring that provides control over technical condition of significant and/or defective structures as well as their standard elements (Kuznetsov, V. M. et al. 2003). Along with inspections (Yekimov, V.K. et al. 2004), monitoring not only gives the information on a structure condition but also helps to observe the behavior of changes of the condition state in time so that prompt measures of repair and rehabilitation are timely taken to ensure the reliable functioning of a given bridge facility.

Nevertheless, monitoring systems are mostly unique and not in daily use, for which at least three reasons exist:

- monitoring equipment is expensive and is not easy to install, while in several cases installment is only possible when erecting a structure itself (we can mention as an instance the continuous monitoring system “SOFO” (ZAO “Mogormash”. 2003), which based on the fiber optic principle that necessitates building of fiber optic transducers in the structure during the construction stage).
- complexity of processing of large arrays of continuously incoming data and lack of the relevant optimal mechanisms of decision-making.
- multi-function instrumental systems designed for this purpose are only few in number.

So, in the global practice continuous monitoring is employed on rare occasions, mostly with reference to highly specific tasks, e.g. in cases when:

- impact (suddenly-applied) loads are possible due to non-standardized passing of standard weights or for geophysical (e.g. seismic) reasons;
- accelerated deterioration of the structure is observed but the reasons for that are not quite clear;
- it is desirable to fix the instant of failure for some elements that protect the structure (e.g. expansion groove), or overriding of acceptable values of failure parameters (e.g. crack opening displacement);
- it is necessary to obtain special information for research purposes.

With the intent to eliminate above mentioned drawbacks, we propose a method of long-term bridge monitoring with the use of mobile instrumental measuring system. Such system does not require any sophisticated engineering works for its installation and operation and may be used in various facilities. Very important in this case is the system of large data array processing that helps analyzing the trends of parameter changes of individual elements and forecast the structure condition as a whole.

This system is based on the technology of continuous measurement and recording of physical parameters. Schematic diagram of the equipment suitable for the implementation of such technology is shown in Fig.1, the centerpiece of which being Data Logger (DA) that continuously or periodically scans transducers and accumulates measurement data in on-board memory for further analysis (Brodski, G.& Shmarian, E.M. & Gavinski, Y.A. 1986.). It is understood that transducers as well as data Logger should have reliability and robustness at the level that ensures their continuous operation in real operating conditions for the equipment being controlled.

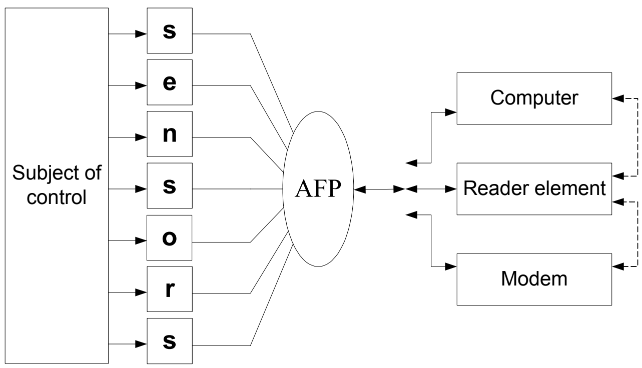

Figure1. Schematic diagram of Continuous Measurement and Recording of Physical Parameters.

For the provision of hardware support of the technology of continuous measurement and recording of physical parameters with the purpose of studying the structure behavior the authors have developed a Data Logger of a special type - AFPγ (Analyzer of Physical Parameters).

AFPγ device has been built on the base of reprogrammable microcontroller with eight-channel analog-to-digital converter (ADC) equipped with nonvolatile real-time clock, 512KB on-board memory, RS232 serial interface for communication as well as analog and digital inputs (outputs) for connecting incremental transducers.

Presence of reprogrammable Flash-Microcontroller provides flexible variation of AFPγ operation mode subject to processing option related to data received from analog/digital inputs. For instance, if signals are to be logged for each channel with a predetermined time intervals and saved in the device non-volatile memory, the device operates as an electronic recorder (graphical interpretation of measurement results is given in Fig.2).

With the use of AFPγ it is possible to determine a structure exposure time in a certain condition under a given load or in various critical conditions. In this case, the device functions as a data logger. Number of levels (intervals) of the bar chart is defined by setting (for AFPγ – maximum 10). Graphical interpretation of measurement results for this case is represented in Fig.3.

Operation in combined modes “Recorder +Data Analyzer” and “Data Logger +Data Analyzer” may be possible as well.

Whichever the case, data communication is made via RS232 interface, PC or with the use of an intermediate communication device equipped with an alfa-numerical display for quick evaluation of read data. More complex devices (modems and converters) may also be utilized for repetitive sending data from AFPγ to a remote control unit via telephone or cable line.

AFPγ device is invariant to the transducer type used so long as their output signal is within the specified range and, accordingly, is suitable for the solution of a diversify of tasks, e.g. when taking measurements of:

- strength parameters, e.g.: strains, pressures, stresses;
- kinematic parameters, including rotation angles, deformations, velocities and accelerations;

- climatic parameters, such as temperature, humidity, wind velocity and direction;
- electrical parameters, such as voltage and current.

Certainly, it takes the utilization of the relevant primary transducers. At present, a vast range of transducers is being produced, however, for their use most of them require adaptation of bridge design associated not only with the selection of output parameters but also with the environmental protection, power supply, acceptable assembly conditions, etc.

A special kit of primary transducers is developed for operation in conjunction with AFPγ device. Their data are represented in Table 1. Transducers comprising the kit are hermetically sealed, which ensures both protection from physical damage and high measurement repeatability within the wide range of ambient temperatures. The transducers do not interfere each other or any other devices.

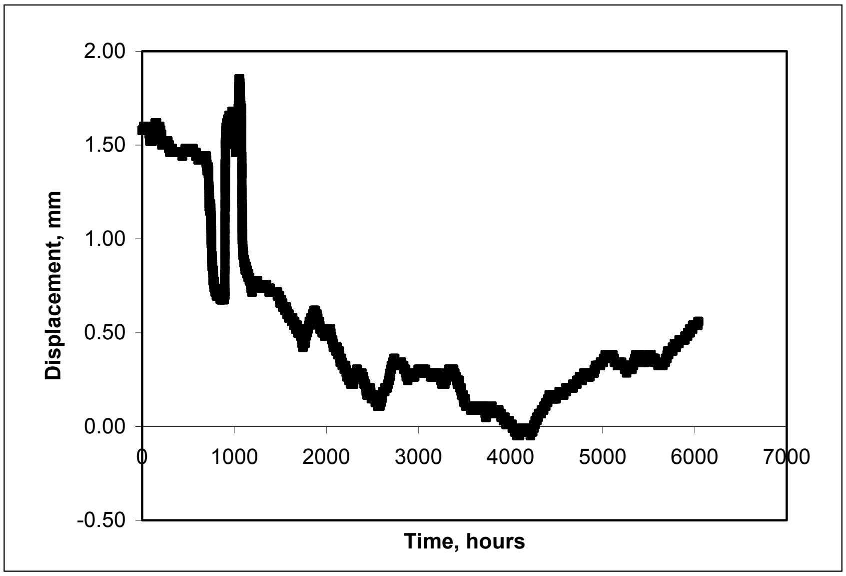

Figure2. Graphical representation of AFPγ measurement results in Electronic Recorder mode in terms of temperature measurement (primary transducer - Omega 44030 thermistor).

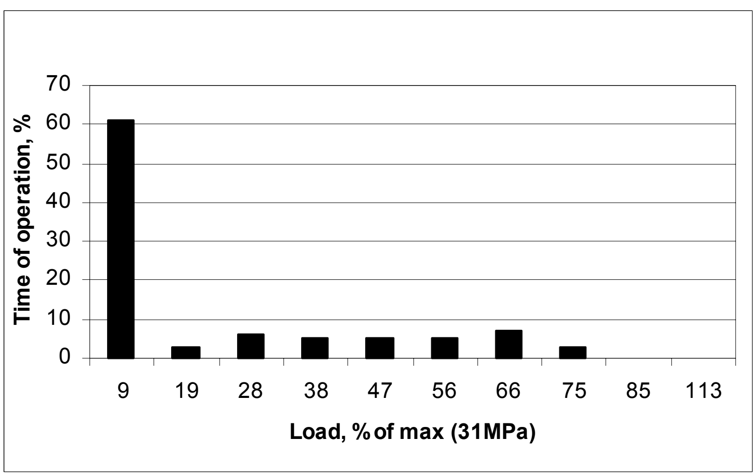

Figure3. Graphical representation of AFPγ measurement results in Data Logger mode in terms of the liquid differential pressure (primary transducers– MD-400P).

In case the distance from a primary transducer to the Data Logger exceeds the maximum allowance, especially matched transmitters designed for the amplification and stable transmission of electrical signals are to be used.

Operation of the continuous monitoring systems on Moskvoretsky and Avtozavodsky Bridges in Moscow during 2002–2004 has manifested satisfactory reliability and operational stability. The example of the data obtained is shown in Fig.4.

Table 1. Basic technical data of transducers (certified by ROSTEST)

Main sensor type	Measured parameter	Measurement range	Output signal	Measurement error	Temperature range	Power supply
SCD-SE	Linear Displacement	0–12.5mm 0–2.5mm	0–5V	0.25%	–25 °C… +85 °C	+8.5…28V
RVIT	Angular Displacement	±60°	± 3V	0.35%	–25 °C… +85 °C	+5V
3274-10K	Load	5t max.	2±0,25% mV/V	±0.10%	–18°C … +120°C	20V
3274-20K	Load	10t max.	2±0,25% mV/V	±0.10%	–18°C …+120°C	20V
3275-1010-50K	Load	25t max.	2±0,25% mV/V	±0.10%	–18°C… +120°C	20V
3277-101-200K	Load	100t max.	2±0,25% mV/V	±0.10%	–18°C… + 120°C	20V
EE06	Rel. Humidity, Temperature	0-100%RH –40…+60 °C	0–1V		–40 °C… +60 °C	+4.5…30V
EE65	Wind Velocity and Direction	0–20m/sec.	0–10V	0.3m/sec.+ 4%	–20 °C… +50 °C	24 B
44030	Temperature	–40…+75°C		±0.1°C	150°C max.	None

The use of continuous monitoring system on said bridges resulted in an enormous amount of data, which was difficult to promptly process and analyze. The proposed primary data processing method is to allow the user to have a concise data in a visualized form convenient for further analysis. Meaningless data was rejected based on comparison of adjacent readings and the measurement error. Identification of doubtful values was made by statistical data processing using adjustable error criteria.

Information received from the Data Logger are data arrays convertible with the use of a special software NIKA, which is the part of AFPγ kit. Each array contains measurement date, measurement time and results for each channel represented as electrical current magnitudes. This primary spreadsheet is saved as a file. Then instrument readings are converted from electrical measurement units (volts) to directly measurable value units (e.g. mm, °C, etc.) following which they are analyzed with a view to obtain a compact data array convenient for further processing.

Data array volume shrinkage is performed by exclusion of repeated values with due account for the measuring system inaccuracy as well as the exclusion of known invalid data from the array.

Measuring system inaccuracy is estimated as the sum of inaccuracies of the transducer and Data Logger:

$$\Delta_{sys} = \Delta_{acc} + \Delta_{trans} \quad (1)$$

Thus, linear displacement transducer inaccuracy with 2.5mm range and 0–6V output signal is 25% of full scale, i.e.:

$$\Delta_{trans} = 0.25*2.5/100 = 0.00625\text{mm}. \quad (2)$$

Data Logger inaccuracy with 2.5mm range and 0–10V output signal and 256-bit capacity when operated in combination with the said transducer will be:

$$\Delta_{acc} = 2.5/[6/(10/256)] = 0.01666\text{mm}. \quad (3)$$

Hence, total instrument error will be Δ_{sys} = 0.00625+0.01666 = 0.02291mm

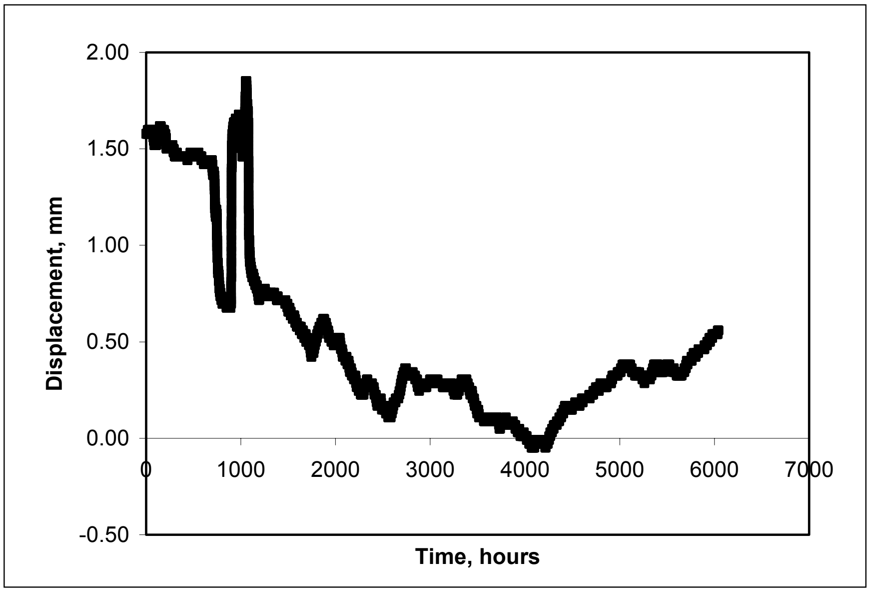

Figure 4. Time displacement variation diagram based on measurement results on Moskvoretsky Bridge.

When processing the whole array of data received from Data Logger the data falling into the measurement error interval is excluded. Each subsequently measured value is then compared with the previous one and, if the difference falls into the system error interval such value is discarded. Alternatively, if the difference exceeds the range then the value is retained and the subsequent value is compared with a first value, not with the second one. Such screening-out of the results helps substantially reduce output data volume.

To facilitate further analysis of the obtained data statistical processing of data is conducted and its results are represented in a file (Ventzel E.S.& Ovcharov, L.A. 2000). An illustration below is a sample from the table of statistical processing of output data obtained from a linear displacement transducer installed on a dilatation joint of Moskvoretsky Bridge (Table 2).

As seen from Table 2 "doubtful" data, i.e. data for which the condition:

$$m\delta-3\Sigma\delta<\delta i<m\delta+3\Sigma\delta \quad (4)$$

is not met are not excluded but retained in the Table for further expert analysis. Such screening-out of the output data array is held for each measurement channel.

Processing efficiency can be determined as shown in table 3. For instance, processing of output data array obtained during Moskvoretsky Bridge monitoring allowed to reduce data array size from 9,701 down to 314 strings, i.e. screening rate amounted to 96.76%.

Detailed comparison of curves based on "processed" and "raw" data array demonstrated that no data corruption took place during the processing, only "noise" was eliminated instead, i.e. peaks were cut by an amount exceeding the measurement error (Fig.5).

In order to reduce labor input related to the results processing and normalization of data for further analysis a special software “NIKA” had been developed to meet the following tasks:

- receiving files in standard formats;
- conversion of electrical measurement units into directly measurable value units;
- saving initial data received from the Data Logger as individual files and updating the existing files with new data;
- primary screening-out of data falling into the total instrument error interval;
- calculation of statistical characteristics, such as expectation, dispersion RMS deviation, variation coefficient.

NIKA also provides usual services, like calculation of algebraic data functions, plotting various diagrams, etc.

Table 2. Sample of statistical processing of output data

Interval, Hours	Interval, Hours	Displacement t	δ	Expectation δ	Dispersion δ	Whether condition mδ-3Σδ<δi<mδ+3Σδ is met:	Date	Time
0:00:00	0	2.696078					Feb. 11, 2003	5:14:14
52:15:00	52	2.892157	0.196079	0.000193	0.000036	Yes	Feb. 13, 2003	9:29:14
52:30:00	52.5	2.892157	0.000000	0.000000	0.000000	Yes	Feb. 13, 2003	9:44:14
92:45:00	92	2.696078	-0.196079	-0.000193	0.000039	Yes	Feb. 15, 2003	1:59:14
93:00:00	93	2.696078	0.000000	0.000000	0.000000	Yes	Feb. 15, 2003	2:14:14
154:15:00	154	2.892157	0.196079	0.000193	0.000036	Yes	Feb. 17, 2003	15:29:14
154:30:00	154.5	2.892157	0.000000	0.000000	0.000000	Yes	Feb. 17, 2003	15:44:14
278:45:00	278	2.892157	0.000000	0.000000	0.000000	Yes	Feb. 22, 2003	19:59:14
....	....	....	....	....	....	....	....	....
526:04:51	526	6.421569	3.529412	0.003470	0.012224	No	March 04, 2003	3:19:05
731:58:31	731	6.617647	0.196078	0.000193	0.000036	Yes	March 12, 2003	17:12:45
....	....	....	....	....	....	....	....	....

Expectance δ	0.003567
Dispersion	0.466197
RMS Deviation	0.682786
3Σδ	2.048359
mδ-3Σδ	–2.044792
mδ+3Σδ	2.051926

Table 3. Processing efficiency for meaningless and doubtful data sorting

		Screening Rate, %	Doubtful Data No	Doubtful Data %
Initial Array Dimension, number of strings	N			
Transducer 1 Array Dimension, number of strings	n_1	$n_1/N*100$	a	a/n_1*100
Transducer 2 Array Dimension, number of strings	n_2	$n_2/N*100$	b	b/n_1*100
Transducer 3 Array Dimension, number of strings	n_3	$n_3/N*100$	c	c/n_1*100
Transducer *i* Array Dimension, number of strings	n_i	$n_i/N*100$	m	m/n_1*100

Thus, a user will be able to obtain the monitoring results not only in the form of tables containing fixed time and electrical signal values but in the form convenient for further analysis as well.

As an example of measurement data interpretation below is a conversion of transducer plunger movement installed on Moskvoretsky Bridge into deflection values.

Conversion method is based on a three-dimensional analysis showing linear relationship between the movements in the arch elements and movements measured by the transducers.

Set of equations for movement determination is given by:

$$\begin{cases} d_l = K_l^{\Delta l} * \Delta_l + K_l^{\Delta tl} * \Delta_{tl} + K_l^{\Delta t^o} * \Delta_{t^o} + K_l^{\Delta r} * \Delta_r \\ d_k = K_k^{\Delta l} * \Delta_l + K_e^{\Delta tl} * \Delta_{tl} + K_k^{\Delta t^o} * \Delta_{t^o} + K_k^{\Delta r} * \Delta_r \\ d_r = K_r^{\Delta l} * \Delta_l + K_r^{\Delta tl} * \Delta_{tl} + K_r^{\Delta t^o} * \Delta_{t^o} + K_r^{\Delta r} * \Delta_r \end{cases} \quad , \qquad (5)$$

where d_l, d_k and d_r = measured movements on transducer locations (left abutment, key abutment and right abutment, respectively); Δ_l and Δ_r = movements determined by horizontal movements in the abutments; Δ_{tl} = movements determined by a temporary load action; Δ_{t^o} = movements determined by temperature differences; Ki^j = proportion factors of unit deflections; to be determined based on a finite element representation**.**

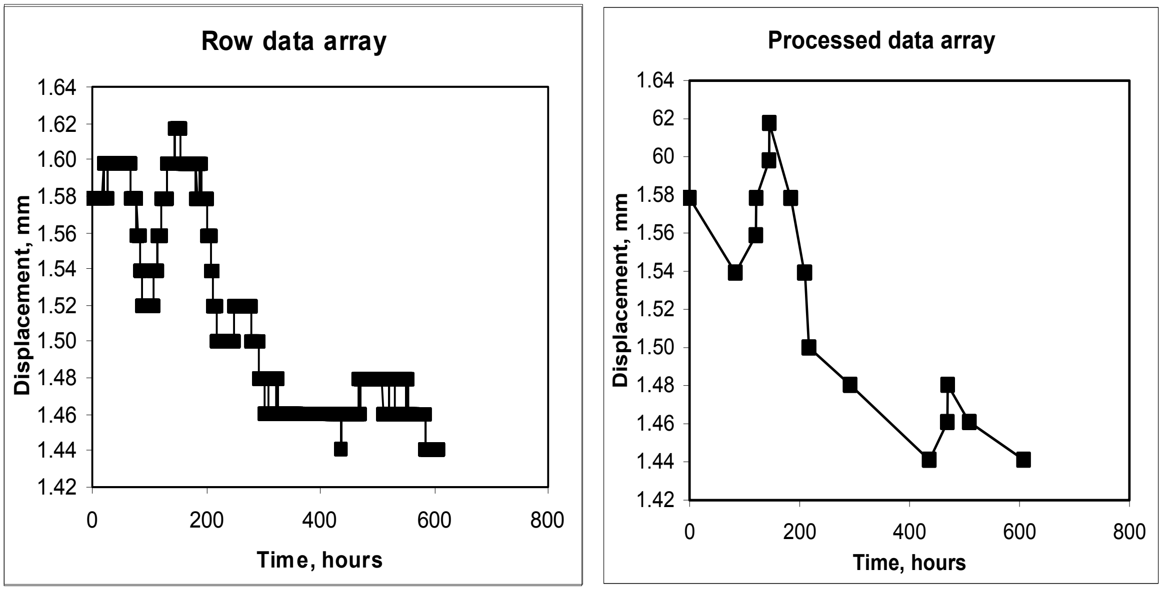

Figure 5. Detailed comparison of the transducer SSE2.5 #1 plunger movement for 600 hours of operation.

Whereas

- temporary traffic loads under heavy traffic are uniformly distributed;
- single heavy temporary loads on this bridge are improbable as well as their logging by the transducers with a scanning frequency exceeding 0.5 hours;
- deflection (camber) of the arch key caused by a temporary load is far less than the deflection (camber) caused by temperature difference;
- thermal effect is symmetrical by nature and is substantially similar to a uniformly distributed load;
- control geodesic surveys verify the resultant effect from a temporary load and temperature difference,

hence we can assume that $\Delta_{tl} + \Delta_{t^o} = \Delta_v$, where Δ_v = vertical displacement in the joint. Then the set of equations takes the form:

$$\begin{cases} d_l = K_l^{\Delta l} * \Delta_l + K_l^{\Delta v} * \Delta_v + K_l^{\Delta r} * \Delta_r \\ d_k = K_k^{\Delta l} * \Delta_l + K_k^{\Delta v} * \Delta_v + K_k^{\Delta r} * \Delta_r \\ d_r = K_r^{\Delta l} * \Delta_l + K_r^{\Delta v} * \Delta_v + K_r^{\Delta r} * \Delta_r \end{cases} \quad (6)$$

Unknown magnitudes in the equations above are directly monitored by the displacement sensors installed on the Moskvoretsky bridge.

Continuous monitoring of the arch displacement on said bridge allowed to discover discreetness and hysteresis in the work of the upper joint.

As a result of the year-long monitoring it was found that the vertical displacements (40-50 mm) in the joint were only of seasonal character. Horizontal movements in the arch abutments varied from 2 mm to 5 mm. Furthermore, unsatisfactory performance of the key joint was identified. It had manifested in discrete and delayed movements of up to a few hours as compared with the joints at the arch abutments. Significant difference between structural depressions on North and South sides of the span had been also notified.

According to the information obtained the replacement of the joints was fitted into the major repair schedule of 2006-2007.

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