METHOD OF STRUCTURAL MONITORING FOR SYSTEMS WITH AN IMPERFECT SENSOR NETWORK

Authors:

Prof. Dr.-Ing. Gennadii Boldyrev
Dipl.-Ing. Pavel Nesterov

Corresponding Author: **G.Boldyrev**

440068 Penza, Centralnaj, 1, Russia

Phone: +7-8412-381744

E-mail: g-boldyrev@geoteck.ru

ABSTRACT

There are important objects behind which constant supervision (monitoring) is necessary. According to regulations, on such objects the structured systems of monitoring and management of engineering systems of buildings and constructions are subject to obligatory installation. They provide supervision over the basic systems of object, using a network of geodetic and geotechnical sensors. This network, being the basic source of data about an object state, itself has defects.

Nowadays not monitoring of limiting values, but revealing of tendencies becomes the purpose of the stress-strain analysis. With highest resolution and highest recording rate of current instruments the small deformations, caused by the daily temperature changes, can observed. These disturbances are present in the readings of all sensors and, therefore, may appear in the cross-correlation relations. If correlation dependences of a sensor or group of sensors with the majority of others is weakened it testifies to abnormal behavior either sensor, or object.

Propose the method of supervision, which map changes in object-network state (behavior) into subspace of correlation characteristics of groups (associations) of sensors with strong correlations. The method provides supervision of changes in object-network state, it is insensitive to the spread in biases and gains of sensors, up most of defects in the network, at the same time, it is identifies and locates drifting and freezing sensors.

Presents the results using the method for long-term monitoring constructions covered sports arena.

INTRODUCTION

There are significant objects, for which is necessary constant supervision (monitoring). In accordance with the existing standards for the early detection of abnormal changes in the stress-strain state, unique building should have a fixed monitoring system operating in the automated mode [1].

G.G. Boldyrev and P.V. Nesterov are with Research and Production Company (NPP) Geotek Ltd., 440068, Tsentralnaya st. 1, Penza, Russia.

Monitoring methods and monitoring technology based on the analysis of threats to the object and comparing current stress-strain state with limits. Calculations by this method are standardized and are the basis for determining the strain-stress state of the structures [2]. The calculations use the software products whose algorithms are usually oriented on the finite-element modeling. The obtained data inherently are only estimations and suffer from many assumptions.

Current values of the stress-strain object state monitoring system receives as a time series readings of sensors placed on the elements of design. Experience of deploying and exploitation of monitoring systems shows, that the network of sensors must be enough representative (hundreds of sensors) to cover main structure elements of such unique object as a sports complex [3, 4].

When configuring a system necessary locate and adjust bias and a gain of each sensor. There are errors due to of imperfection of installation and alignment technology. Even if these operations are done perfectly there are errors due uncertainty in coupling elements. It is hard to come up with calibration scheme, which would remove the problem. For calibration is necessary, as a rule, to relocate sensors, transfer them to the test bench. This is inconsistent with the conditions of exploitation: not saved individual transmission characteristics of connecting elements and do not repeat adhesive joints. Thin-film sensors do not allow rebasing at all.

Use in monitoring systems many heterogeneous sensors that are far from being perfect and hard-to-reach for adjustment and repair, forces to search new approaches and special technologies.

RELATED APPROACHES

One approach is the remote control of sensor characteristic. For example, using the local controller provides remote individual adjustment of bias and gain. However, it remains a source of error: unknown transfer characteristics of coupling elements.

Recently the problem of monitoring are more often solved using geodetic techniques. Robotic total stations (RTS) with automatic target recognition provide the efficient solution for monitoring strain component of structure state [5 - 7].

Geodetic markers do not require periodic access for calibration. Thus, the problem of access to sensors for their adjusting and repair will removed. However, here not all is cloudless. In geodetic monitoring, there are many sources of error. Errors compensated by redundancy in the network of markers and reference points. Such redundancy allows apply equalization procedure: set of the mathematical operations, which carried out for most exact estimations.

These estimates contain components of errors produced by the effects of atmospheric refraction, the instability of RTS locations and instability of reference points. Reference points should be outside of the zones subject to deformation processes and vibration impact. These requirements are difficult for realizing. Monitoring will suffer from the high level of false alarms and as a result to compromise itself.

On the other hand, is it really so necessary to know the absolute characteristic of the state of an object? Indeed, in accordance with the regulations [2] automated monitoring system designed to detect and locate incipient anomalies, and then must be carried out a detailed survey.

APPROACH: SEARCH FOR NOVELTY IN CORRELATION RELATIONS

According to safety regulations [2] automated monitoring systems are intended for detection and localization of arising anomalous phenomena in the stress-strain state of structure. Then detailed investigations should be undertaken.

Therefore, only changes in the sensor readings are of interest. In this case, information redundancy, which is always available in the sensor network, can be use more efficiently. Frequently, this redundancy is not explicit and manifests itself in correlation relationships.

With highest resolution and highest recording rate of current instruments the small deformations, caused by the daily and seasonal temperature changes, can observed. Possible even monitor the errors of climate control system covered sports arenas.

Indeed, even in these "comfort conditions" temperature deformations of constructions lay in a range 50-100 με and they fit at the resolution of current sensors. These disturbances are present in the readings of all strain sensors and, therefore, should manifest in the cross-correlation relationships.

In addition, the correlation processing improves the signal-to-noise ratio, particularly for cross-correlation of time series with a small lag the following relation holds [8]:

$$W = \sqrt{\frac{n}{2}}\frac{z}{z^2+1} \tag{1}$$

where:

z - signal-to-noise ratio at the input of the correlator;

w - signal-to-noise ratio at the output of correlator;

n – sample size.

The curve of a relation w (z) is shown on fig. 1.

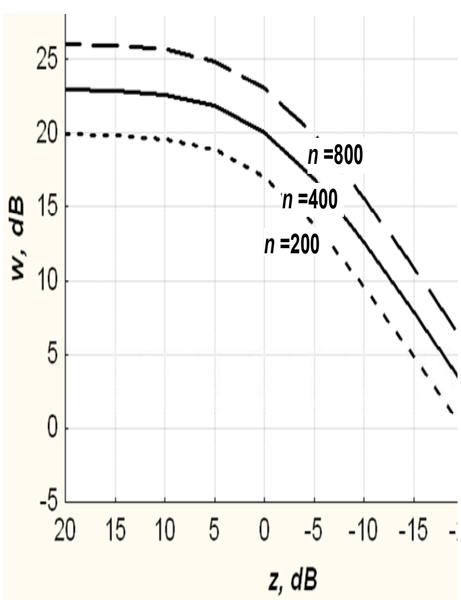


Figure 1. Relation between input and output signal-to-noise ratios of correlator.

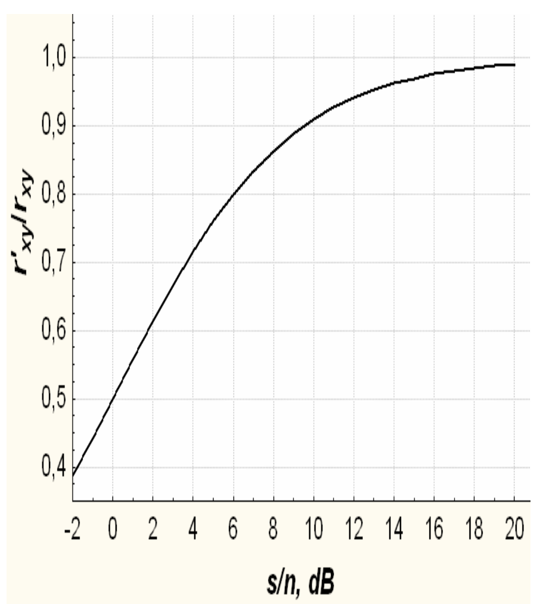


Figure 2. Relation between correlation coefficients and signal-to-noise ratio.

To assess feasibility of the correlation methods can also use the relation that determines the rate of degradation of the correlation coefficient with decreasing the signal-to-noise ratio [9]:

$$r'_{xy} = \frac{r_{xy}}{1 + \dfrac{\sigma_n{}^2}{\sigma_s{}^2}} \qquad (2)$$

where:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - x_m)(y_i - y_m)}{\sqrt{\sum_{i=1}^{n}(x_i - x_m)^2 \sum_{i=1}^{n}(y_i - y_m)^2}}\,;\; x_m = \frac{1}{n}\sum_{i=1}^{n} x_i \;\; ;\; y_m = \frac{1}{n}\sum_{i=1}^{n} y_i \quad ;$$

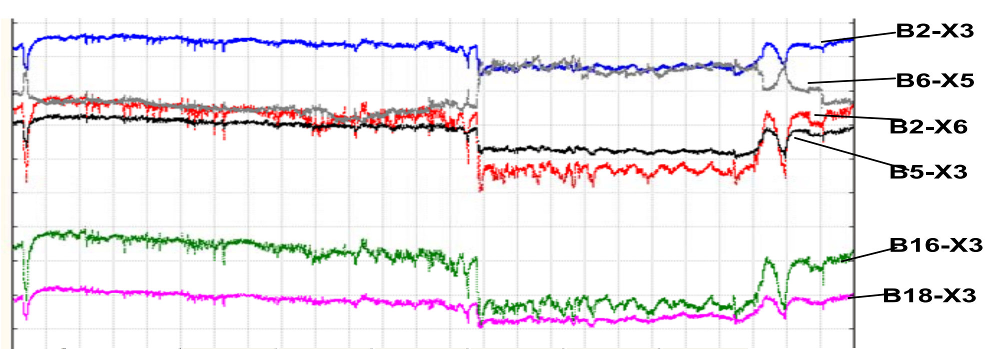
σ_n - standard deviation of signals x and y;
σ_s - standard deviation of noise;
n - sample size

As can be seen from Figure 2, with a signal-to-noise ratio over 20 dB the correlation coefficient practically does not suffer.

The above figures and monitoring practices [3, 4] allow assert, that observation of objects in space of correlation characteristics is realizable.

Matrix of cross-correlation coefficients of sensors is the mixed pattern. There are groups of sensors with direct relationships and with inverse relationships. There are groups with the appreciable time lags.

Correlation coefficients mask such defects of sensors as spread biases, the spread gains and the spread transfer ratios of coupling elements. From Figure 3, it can be seen that strain sensors B2-X3, B6-X5, B2-X6, B5-X3, B16-X3 and B18-X3 (a sport arena "Arena", Omsk, Russia) differ in biases and in gains, however, the correlation relations between them strong and is characterized by a coefficients 0,988. The inverse relationships changes a sign of a correlation coefficient, however, there are no problem if to use a determination coefficient.



sensors	Б2-Х3	Б2-Х6	Б16-Х3	Б18-Х3	Б5-Х3	Б6-Х5
Б2-Х3	1,000	0,988	0,983	0,975	0,977	-0,898
Б2-Х6	0,988	1,000	0,988	0,970	0,979	-0,901
Б16-Х3	0,983	0,988	1,000	0,974	0,992	-0,907
Б18-Х3	0,975	0,970	0,974	1,000	0,960	-0,826
Б5-Х3	0,977	0,979	0,992	0,960	1,000	-0,900
Б6-Х5	-0,898	-0,901	-0,907	-0,826	-0,900	1,000

Matrix of correlation coefficients

Figure 3. Correlation mask spreads in biases and sensor gains.

MONITORING AS A DETECTION OF ANOMALIES (NOVELTY)

For use in monitoring system suggests the following method of tracking changes in the object-network state:

1. Sensors combined into groups (associations), with significant correlation coefficients, for example, more than 0.7. There are various algorithms for finding such groups, for example, the algorithm using principal component analysis, but algorithms based on method of permutation for reducing the bandwidth of sparse symmetric matrices [10, 11] are more interactive and less expensive (do not require intensive computations);
2. Changes in the object-network state traced in changes of correlation relationships of sensors with respect to group. Such relationship characterized by "coefficient of multiple correlation", however, the procedure for the calculation of this coefficient is cumbersome and associated with a risk of failure if the relationship is functional. In practice it is possible to use the estimations formulated as follows: «the coefficient of multiple correlation majorize any pair or partial correlation coefficient" and "a coefficient of multiple correlation can be define as a maximum value of a usual pair correlation coefficients between a variable and other members of a group». The reference given above, justifies use of estimation by mean, which though is underestimated, but is convenient in application:

$$\tilde{R}_i = \frac{\left(\sum_{j=1}^{p} R_{ij}\right) - 1}{p - 1} \tag{3}$$

where:

$\tilde{R}_i$ – is average value of determination coefficient *i*-th variable (readings of *i*-th sensor) with respect to other variables in a group;

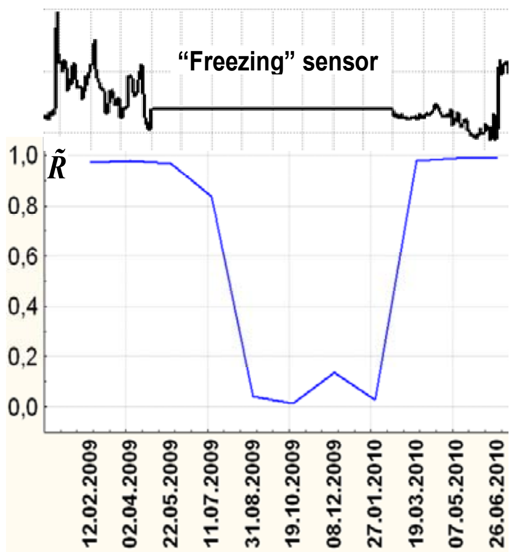
R_{ij} - is determination coefficient *i*-th variable (readings of *i*-th sensor) with respect to *j*-th variable (readings of *j*-th sensor) in a matrix $p \times p$ of determination coefficients;

p – is number of members in a group;

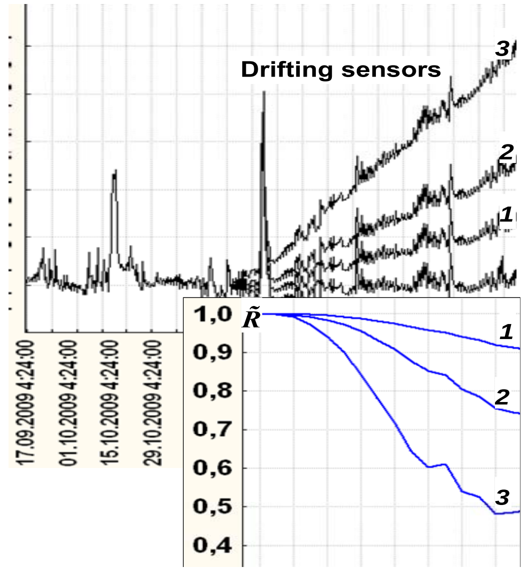
3. With the purpose of dating events (changes in state) correlation characteristics computed in the sample as a moving time window. Figure 2 illustrates as the moving window reveals malfunction in a sensor readings ("freezing"). After recovering of sensor, sharp increase of determination coefficients (3) observed.

It is necessary to emphasize the important property of the characteristics calculated in the moving time window: they allow estimate dynamic of event. Figure 4 shows how the changes in the coefficient (3), obtained by using moving time window, detects the birth of the drifts and displays their slopes;

4. Simultaneous decrease of the coefficients (3) for the subgroup from the group of sensors means weakening of association with temperature variations and shows the anomalous behavior of some elements of the construction. The topology of subgroup allows locate these elements;



Sensor fault: "freezing"



Sensor fault: drifting

Figure 4. Computing in a moving time window reveals sensor faults.

5. Group formed at certain horizons of the object history can serve as a pattern of the object-network behavior, for example, can revealed groups of sensors that are sensitive to changes in some of the operational load on the structures.

APPLICATION: LARGE-SCALE SYSTEM

The developed method used for monitoring the state of covered sports arena ("Arena", Omsk, Russia) [4]. The monitoring system has a dense network of sensors: strain, temperature and tilt.

Software tools that implement the proposed approach include algorithms:

- data processing in the moving time window;
- data smoothing;
- reducing time series lag;
- calculation current correlation matrices;
- calculation current determination coefficients;
- estimation changes of object-network state;
- forming and permuting sparse matrices.

Matrices and determination coefficients are stored as snapshots of object history and used by experts to identify associative groups of sensors.

Monitoring the sports complex started winter 2009. During observations revealed associative groups that are sensitive to changes in the operational load on the structures, in particular, was identified group sensitive to changes in snow load (Figure 5). It used as a template for monitoring the intensity of the snow load (Figure 6).

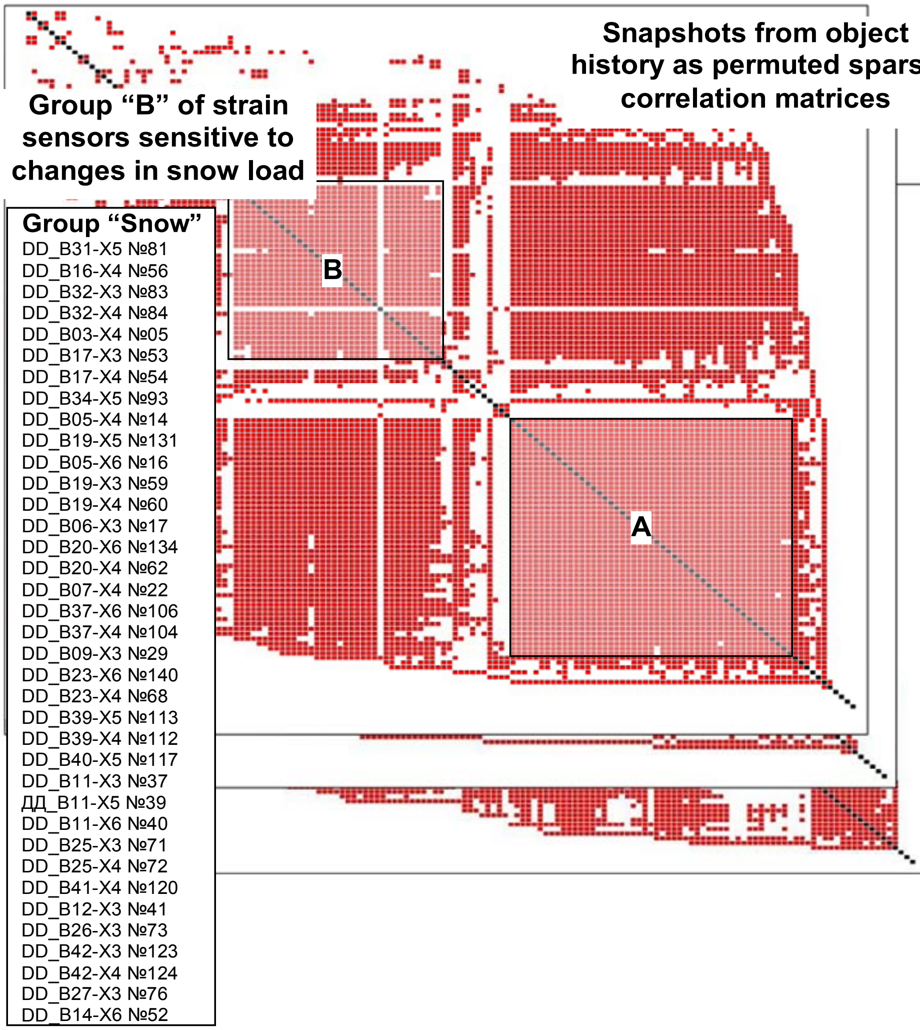


Figure 5. Group of strain sensors sensitive to a snow load ("**B**") (Arena, Omsk, Russia).

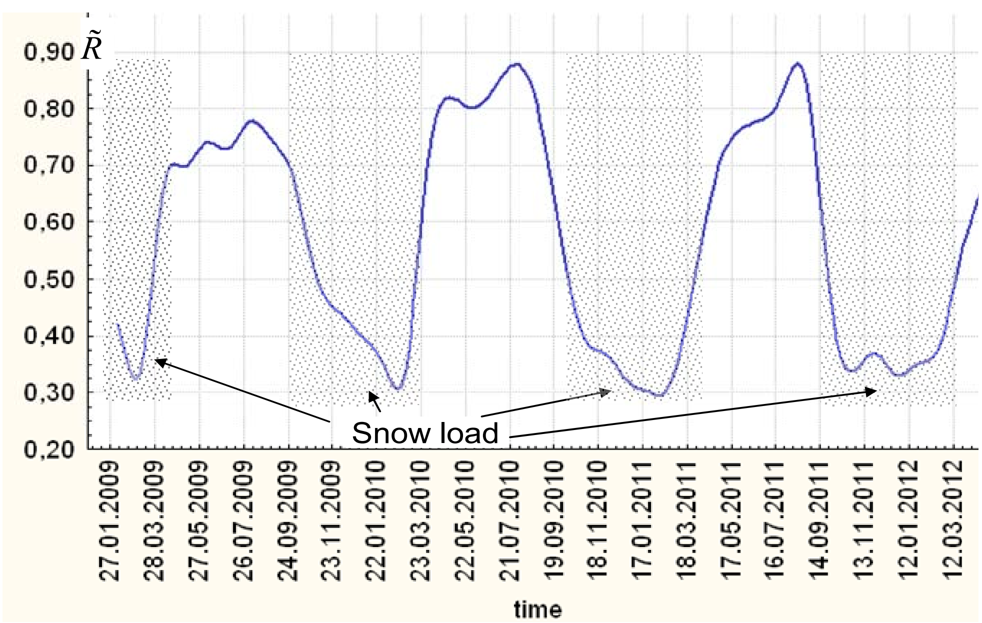


Figure 6. Snow load in space of correlation characteristics (Arena, Omsk, Russia, 2008-2012).

CONCLUSON

The proposed method tested for 5 years in the monitoring system with imperfect sensor network ("Arena", Omsk, Russia) [4]. Most of the flaws are due to the spread in biases and gains of sensors. Experience has shown that method allows an order extend the calibration interval.

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