High-precision smart system on accelerometers and inclinometers for Structural Health Monitoring: development and applications

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***Abstract*—*The Structural Health Monitoring system with high accuracy is presented. The system is based on super high sensitive accelerometers and inclinometers of Floated servo type or precise, but relatively inexpensive Q-Flex servo type as the sensors. The principles of our system design and methodology are explained within. Numerous experiments on application of the developed system for inspections of structural condition of buildings, bridges, etc. in Russia, China and South Korea are discussed. The means to identify resonances, inadmissible for structures are outlined.*

Keywords—Structural Health Monitoring system, building structures, bridges structures, spectral analysis, accelerometer, inclinometer

I. Introduction

The recent increase in number and scale of industrial disasters has caused universal stiffening of requirements applied to buildings', bridges', and other constructions' condition monitoring. These requirements have been tightened in all countries with developed infrastructure, including Russia. Structural Health Monitoring proved to be the key technology for determining the condition of structures and detecting its damage. Various concepts and types of sensors for Structural Health Monitoring systems have been introduced [1-5].

The current shift of Structural Health Monitoring research away from traditional wired methods towards the use of wireless smart sensors has been motivated by the attractive features of the latter ones. One of the important disadvantages of wired monitoring systems is economic inefficiency in terms of installation, maintenance, and management of existing wired monitoring systems [1-5].

The most appropriate sensors for Structural Health Monitoring proved to be the accelerometers and inclinometers. Accelerometers are able to measure changes in the dynamic characteristics of the structures to evaluate the damage that has occurred in the structures. Inclinometers can evaluate the deformation of structural elements using the angles of rotation by determining the vertical deflection via the angle of rotation in the case of horizontal elements and the drift in the case of vertical elements. Smart sensors are considered the more advanced instruments for modern Structural Health Monitoring systems owing to their computerized control abilities [1-5].

Many researchers use micro-electro-mechanical (MEMS) accelerometers in Structural Health Monitoring systems. But these cheap devices are still not sensitive enough and very noisy, therefore, for the determination of vibration frequencies of the structure, it is necessary to arrange a special experiment (for example, causing the structure vibrations by strikes). MEMS devices do not allow for accurate determination of small angular movements of the structure. But spasmodic angular deviations are especially dangerous, so it is required to detect them early to ensure safety of the structure.

We began our researches in early 2000 and decided to use precise and relatively inexpensive accelerometers and inclinometers of Floated servo type or Q-Flex servo type as the sensors [6].

II. Principles Of Design And Choice of Sensors for the Structural Health Monitoring System

A. The Main Approach of our Structural Health Monitoring System

We designed our Structural Health Monitoring system on the basis of modern principles, applying smart wireless sensors [6].

We analyzed typical problems of other researchers which had prevented direct replacement of wired sensing systems with wireless sensor systems and had limited implementation of the last ones considering previous users' complaints [2, 4]. As it is emphasized in [4], one of the most common sensors employed in Structural Health Monitoring strategies is the accelerometer; however, most applied accelerometers have inadequate resolution for measurement of the typical accelerations occurring in many Structural Health Monitoring applications.

In contrast with common ways, we have chosen super high sensitive or precise accelerometers and inclinometers, created the special design for systems to keep the temperature stable,

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and developed methodology and software to calculate data and to correct errors due to sensors' drifts and noises.

First of all, to reach required accuracy of measurement we used super sensitive Floated-type inclinometers and accelerometers with the resolution of 0.001 arc sec and long-term zero stability better 0.1 arc sec. They are extremely expensive, and therefore cannot be considered as devices for the mass production. For other version of system we used quite precise, but much cheaper and easier available on the market Q-Flex accelerometers and inclinometers which have the required resolution of 10 mkg (2 arc sec), but their long term instability of the zero signal is ten times more than the allowable level of 5 mkg (1 arc sec) per day.

The vertical accelerometer measures only micro-vibration accelerations relatively 1 g level. These micro-accelerations cannot be measured by MEMS devices.

Thus, the accuracy requirements for accelerometers of the Structural Health Monitoring system are extremely stringent, and even higher than for accelerometers of inertial navigation systems [6-10].

B. Characteristics of our Structural Health Monitoring system's Design

While designing a reliable and market-friendly Structural Health Monitoring system we took into account the circumstances listed below [11-14]:

- Unlike navigation accelerometers with wide range of measured accelerations from tens to 100 g, the Structural Health Monitoring system sensors must have a small range of those (no more than 1.5 - 2 g for a vertical channel and no more than 0.2 g for horizontal channels). This makes possible, by minor changes in the design and electrical circuits of the devices, to increase substantially the signal-to-noise ratio in them, and to reduce the influence of the zero instability of ADC to convert the accelerometers output signal.
- Accelerometers of the horizontal channels of the Structural Health Monitoring system before the measurements are set (with the help of supports adjusting the position of the system basement) to a position in which the projections of the measured accelerations are close to zero. So, there is no influence of the accelerometers scale factors instability on the stability of the output signals.
- Use of the thermostating system for the case with accelerometers is available. This eliminates the zero drift caused by cyclic changes in environment temperature.
- During the monitoring, the devices operate in a continuous regime, and a prolonged warm-up (within an hour) before the start of the measurement is also allowed. That is why measurement results are free from zero drift which could appear due to the unsteady thermal mode of the devices, and zero instability, caused by the on/off processes in the accelerometer.
- The inclinometers zero values after warming up are fixed in the Structural Health Monitoring system before the beginning of measurement, so there are no requirements for memorizing the inclinometers zero values from measurement to measurement. The only essential requirement is that of zero stability for a single measurement to be carried out for an extended period of time without noticeable mechanical and temperature disturbances.

Considering the above-mentioned features of the device operation we designed the high-precision smart Structural Health Monitoring system. Owing to precise accelerometers and inclinometers, computational capabilities and special design, our Structural Health Monitoring system provides accurate measurement of the micro-vibration and angular movements.

The Structural Health Monitoring system was realized in two versions – portable (Fig.1) and stationary (Fig.2).

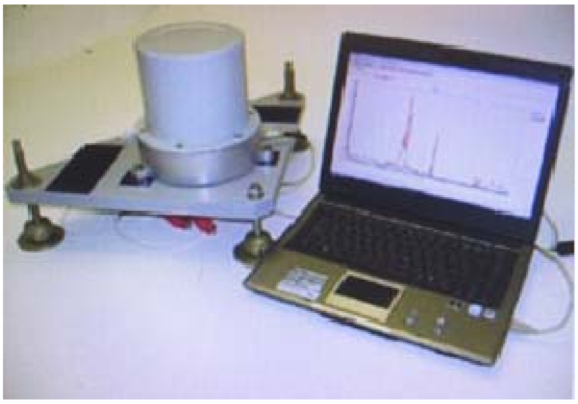

Fig. 1. The Portable Structural Health Monitoring system.

Fig. 2. The Stationary Structural Health Monitoring system.

The Stationary Structural Health Monitoring system involves a microprocessor for the digital signal processing, self-diagnosis, self-tuning functions.

Our Structural Health Monitoring systems were demonstrated at a number of exhibitions of inventions, and were awarded 3 gold medals (Geneva 2005, Nuremberg 2005, Brussels 2006) and Grand Prize (Seoul 2004).

III. Basic Conditions of Application and Specifications of the Structural Health Monitoring System

A. Conditions of Applications and Requirements for our Structural Health Monitoring System

Civil infrastructure is becoming more and more complex and expensive both in construction and maintenance. Last year's notorious disasters made the task of estimation of safety for both infrastructure facilities and evacuation routes, including bridges, overpasses and highways extremely pressing. Every facility has their own features and needs to be inspected for its own risk assessments.

The results of our investigations and tests gave us the following basic information concerning structural behavior and required inspection methods.

- The initial step of inspection has to be the checking of correspondence of the structure's natural resonances to the calculated ones during design. High-quality construction has to preserve that correspondence for a great period of time. Besides the angular movements of the structure that occur when it is loaded, or due to one-side heating by solar radiation, this process must be reversible. The time-dependent angular deviations of the structure relative to the vertical should be absent.

- As our numerous investigations proved, the lower frequencies of vibration are the most indicative on structure condition. These frequencies for most structures fall in the range from 0.005 Hz to 30 Hz. We use accelerometers with a bandwidth of 0 to 200 Hz to get good margin over structural frequency range.

- Levels of vibrating micro-movements arising during exploitation of various structures, as a rule, fall in the range from tens to hundreds of mkg. For this reason, the resolution required from accelerometers and the level of their own instrumental noises (in the frequency range up to 30 Hz) should be lower than 10 mkg.

- Angular movements of structures in the absence of extreme external influences (such as large gusts of wind, etc.) are periodic, caused by solar heating of the structural elements. The amplitude of these movements usually does not exceed tens of arc sec. At night, when the structure is cooling down, the angular position of the structural elements, which does not have accumulated damage, returns to its original position with a repeatability of about 1-2 arc sec. One-sided displacement of the trajectory of angular motion from one daily cycle to another indicates either instability of the foundation, or increasing deformations and displacements of structural elements.

- Especially dangerous is the situation of one-sided repetitive spasmodic angular movements of structural elements.
  Such movements, for example, had been observed during our tests of Voroshilov Bridge in Rostov-on-Don, six months before its emergency destruction which had been predicted by the results of our inspection, as we will describe further (see Part IV,*B*) The levels of above-mentioned micro-movements, measured experimentally, range from unities to parts of arc sec. Monitoring systems' inclinometers should reliably measure such movements, so their resolution should not be less than 1 mkg, and it is required to measure increments of units of mkg and to distinguish it at the level of noise and zero drift of accelerometers.

B. The Specifications of our Structural Health Monitoring System

Our Structural Health Monitoring systems provide the measurement of the tilt angular rate and the structure natural frequencies with the angular resolution of 0.1 arc sec, zero long-term stability of 1 arc sec, the frequency range from 0.005 to 30-50 Hz, the vibration accelerations resolution of units of mkg.

For comparison, the existing monitoring systems, as a rule, have an angular resolution not better 10 arc sec, which is coarser than is necessary for precise inspection of most modern structures, and the vibration accelerations resolution of tens of mkg, which is also coarser by an order of magnitude that is required for distinguishable reliable measurement.

To prove parameters of our Structural Health Monitoring system we test the assembled system on a precise foundation for several days continuously.

Our smart Structural Health Monitoring systems have the computational capability for the self-diagnosis, self-tuning functions and for the signal processing in accordance with our methodology and specific algorithms for each application.

IV. Applications of the Structural Health Monitoring System for Inspection of Buildings and Bridges

The described Structural Health Monitoring systems were used for inspection of numerous constructions, including buildings and bridges in Russia and abroad (in Seoul, Harbin and Beijing). We used precise instruments in our system, but the most important for getting the true impression about the structural condition is the methodology, which we developed for recognizing the defects and predicting the danger of destruction. Our methodology fits for every structure for observing it either under construction or exploitation. Some interesting results of observations are presented further.

A. Inspection of Buildings

While investigating the buildings we tested both compliance of their natural resonances to the pre-calculated ones at the design stage and their behavior at construction and usage stages.

Due to the ultra-high resolution of the inclinometers and accelerometers included in our Structural Health Monitoring system, natural frequencies are reliably detected even in undisturbed structures. Disturbances caused by wind loads, or traffic outside the structure, etc. are sufficient for detecting the slightest measurements.

We investigated two 33 and 43-storey buildings under construction at the residential complex «Severniy park», (Fig. 3).

Fig. 3. Residential complex «Severniy park» in Moscow.

Our inspections showed the compliance of buildings natural resonances to the pre-calculated ones with accuracy 2-3%, that proved a high quality of buildings structure.

We investigated thermal motion of structural elements of the buildings due to heating by solar radiation. Typically it is periodic, and the magnitude of their conical rotation depends on the intensity of the radiation. Usually the amplitude of oscillations with a daily cycle does not exceed two dozens of arc sec. If the structure is stable, conical motions occur around an axis to maintain a fixed position relative to the vertical. Complex «Severniy park» was constructed in the floodplain of Moscow-river, so it was important to check the sustainability of the buildings. We were continuously monitoring the inclinations of the buildings over 24 hours. The results of measurements for the 43-storey building are shown in Fig. 4.

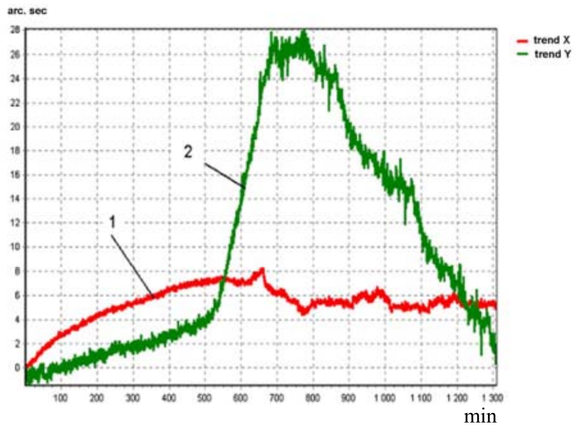

Fig. 4. Measurement of building inclination during 24 hours from midnight to midnight:
1 - inclinations in North-South direction;
2 - inclinations in East-West direction.

Structures were recognized to have maximal deviation from a vertical 15 arc sec for the 33-storey building and 28 arc sec for the 43-storey building. Their reason becomes clear from the graphs Fig. 4 as heating-up of buildings by sunlight during daytime and cooling-down at night. Investigations of the residential complex «Severny Park» have confirmed a high quality of buildings frames construction, and also firmness of their foundations.

B. Inspection of Bridges

While investigating numerous bridges it was found that if bridge's structure sustainable, its natural frequencies remain unchanged regardless of season, traffic and other exploitation conditions.

If during exploitation, the frequency spectrum and/or the quality factor of oscillations change, these are the alarming signals that the bridge structure has sustained a certain amount of damage. Appearance of cracks in the structural elements causes a dramatic increasing the resonance peaks in oscillations. It was proved during our investigations of Krimskiy Bridge in Moscow (Fig. 5) and illustrated by Fig. 6 where the oscillation spectrum is seen to change significantly before and after bridge repair.

Fig. 5. Krimskiy Bridge in Moscow.

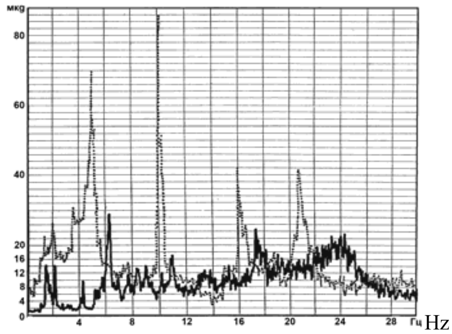

Fig. 6. Krimskiy Bridge: oscillations of the bridge, registered before (dotted line) and after (solid line) repair.

The amplitudes of resonant peaks are being seen to decrease significantly after the repair, and a part of the resonant peaks shifted towards higher frequencies.

To check the condition of the structures it is recommended to carry out periodic monitoring of their natural frequencies and check whether both these frequencies, and the amplitudes of the resonant peaks in the oscillation spectrum remain constant.

We were invited for participation in procedures of Structural Health Monitoring with help of our system in China and in the Republic of Korea.

Monitoring of building structures in the Republic of Korea is being paid particular attention after some terrible catastrophes - the destruction of the large department store and collapse of the automobile bridge in Seoul.

We used our system and our unique methodology and received interesting and important results, briefly presented further.

One of the main problems of bridges is the washout of the land from under the bridge pillars, which can lead to horizontal disruption of the bridge with subsequent defects in structural elements and, as a result, possible catastrophic destruction of the bridge.

The inclinometers included in our monitoring system allow for measurement of the changes in the angle of the base of the monitoring system in time with super-high accuracy: with a resolution of at least 0.2 arc sec and with stability no worse than 1 arc sec per day.

With the help of our system, Bulti Bridge (Fig. 7) in the city of Sejong (the Republic of Korea) was carefully investigated. Certain results of the measurements are presented in Fig. 8 a,b.

Fig. 7. Bulti Bridge, the Republic of Korea.

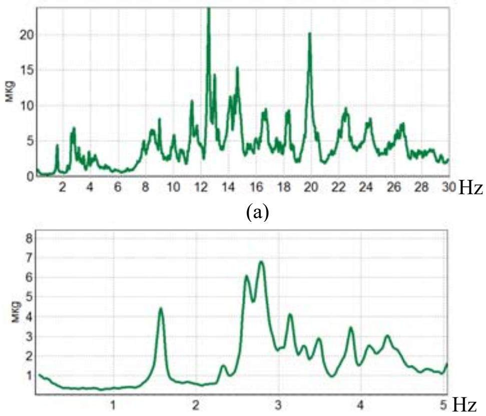

Fig. 8. Spectrum of oscillations of the Bulty Bridge: for wide range (a) and for narrow low frequency range (b): measured natural resonance frequencies at 1.58 Hz, 2.63 Hz, 2.80 Hz, 3.15 Hz, 3.50 Hz, 3.88 Hz, 4.31 Hz etc. coincide to pre-calculated figures with high precision.

Investigations of bridges in the Republic of Korea with our methodology showed detailed spectrum of their structural oscillations. As it is well seen in Fig. 8, our super-precise measurements demonstrated Bulti Bridge's natural frequencies exact coinciding with the pre-calculated figures, that proved good structure condition and sustainability of bridge.

The precursors of a structure catastrophic destruction can be recognized by the accurate monitoring with inclinometers. In the case of developing destruction, there is an increasing deviation of the structure elements from the vertical, significantly exceeding their movement in the daily temperature cycle under the solar radiation. The increasing of slope can be both smooth and stepwise.

While investigating with our Structural Health Monitoring System Voroshilov Bridge through the river Don in the city of Rostov-on-Don we recognized the presence of one-sided directional spasmodic micro-movements of the bridge structure with the amplitudes from unities to tens arc sec. These movements were found while we were controlling the daily movements of bridge structural elements, and were observed at intervals of several hours to days. The Administration of Rostov-on-Don was distrustful of the results of our inspection and after checking the condition of the bridge by traditional methods, the exploitation of the bridge was continued.

The bridge collapsed 6 months later. As it became clear, when destroyed structural elements were inspected, the spasmodic angular movements of elements that had been registered during our monitoring corresponded to moments of rupture of the concrete slabs armature having been rusted due to leaks of salt water used as deicing reagent in the concrete slabs.

Pictures of the bridge, during the test period, and the repair work after the destruction are shown in Fig. 9 a,b.

a) (b)

Fig. 9. Voroshilov Bridge in the city of Rostov-on-Don, Russia before collapse (a) and under repair (b).

Thus, as we proved with our Structural Health Monitoring system, if one-sided deviation of the bridge structure elements is growing, especially when small spasmodic shifts occur or when the angular displacement speed smoothly increases, it is sufficient for sounding the emergency "alarm" signal to close down bridge from public use in a state of danger and immediate detail checking of its condition.

C. Our Methodology Essential: How We Reach Super-High Precision

Our experience of using a mobile monitoring system proved that to obtain a reliable assessment in the analysis of various structures, the sensors resolution of structural elements' vibration (vertical accelerometer and horizontal inclinometers) should be at the level of 1 mkg, and the stability of the inclinometers zero signal should be of 1 arc sec per day and 2-3 arc sec for longer measurement periods (from a month to 6 months). At the same time, devices should have minimum own noise. However, the noise characteristics of the Floated-type and Q-flex devices used in our monitoring systems at a small averaging time can significantly exceed the required resolution. Besides, noise random movements, which may occur in the places of monitoring system installation on the investigated structure, don't correspond to the forms of structural vibrations. These noises can also exceed the required resolution. As a result, the recorded in the tests oscillation spectrum, being plotted by processing information massive for short time periods (about 10 sec), are appeared to be unsuitable for determining the frequencies of the structural oscillation forms. However, with considerations the noises are random, and the structural own vibrations accelerations have a fixed frequency, we average the short spectrum for a time period up to 30 min, and get spectrum corresponding to the maximum resolution of the used devices: for Q-flex devices – about 0.1-0.5 mkg, for Floated-type devices – about 0.01 mkg. Similarly, the influence of noise in the measurement of the structural inclination angles is excluded.

It is much more difficult to ensure the zero long term stability of the monitoring system sensors. Even the best samples of Q-Flex devices (QA-2000, QA-3000), according to the passport specification, do not have the required long term stability. A fortiori, low-cost Q-flex devices of worse quality do not have that. This problem is solved by thermostating the sensors cluster and choosing the measurement method, in which the devices are turned on for 2 hours before measurements. Then, measurement starts only after completion of all types of sensors drifts and are being made continuously with power supply is on. At the same time, the devices are not subjected to any noticeable vibrations and shocks, and also to the cyclic temperature changes during the measurement. It was proved that under these conditions, inexpensive Q-flex devices are able to provide zero long-term stability at the level of 0.3-0.5 arc sec. Taking into account the operating conditions of the devices in the Structural Health Monitoring Systems, navigation-type accelerometers that do not meet full requirements of navigation systems can be applied in the first ones. The required small range of measured accelerations (1.5 g for vertical accelerometer and 0.2 g for inclinometers instead of 50-70g for navigation-grade devices) is provided by demagnetization of magnets in the assembled sealed devices. Such devices are much cheaper than accelerometers of navigation-grade sensors.

V. CONCLUSION

Presented Structural Health Monitoring system is a universal device applicable in many situations arising in the exploitation of buildings, bridges and other structures.

Our monitoring system was developed so that it provides extra high measurement accuracy even with the relatively inexpensive Q-Flex accelerometers and inclinometers.

High resolution of our devices, as well as our unique methodology, which reduce the instrumental noise at the output to the level of 0.1 mkg, provide the reliable measurements of the acceleration of micro-movements of structures without special disturbing actions (strikes). The results of the measurements were processed with plotting the spectrum to determine the frequencies and amplitudes of structure's natural oscillations for matching them against pre-calculated figures and for forecasting the structure's behavior.

In addition, horizontally oriented accelerometers (inclinometers) detect very small angular movements (up to a fraction of the arc sec during the day and up to 2 arc sec per month of measurement), that will indicate dysfunctional situations in the early stages of arising destruction.

With help of our system, the monitoring of a large number of structures was carried out and either their good condition was confirmed, or a pre-accident situation was revealed, which later may lead to the collapsing of the structure.

Great experience in monitoring various buildings, bridges, TV towers, tunnels, underground gas storage facilities, allowed us to develop an effective and universal high-precision smart system on accelerometers and inclinometers for Structural Health Monitoring. Further we plan to enlarge the capabilities of our system.

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