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SEISMIC MONITORING OF LINEAR AND ROTATIONAL OSCILLATIONS OF THE MULTISTORY BUILDINGS IN MOSCOW

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Abstract. *The specially designed seismic monitoring system is deployed on high-rise buildings in Moscow. The system is capable of recording of the natural oscillations of the structures, with special attention to the angular motions, data processing to recover the natural motions from the micro seismic background noise and comparison of observed and theoretically predicted motion modes. Based on the comparison results the more accurate theoretical models and its software realizations for the building behavior can be developed. Both linear and rotational oscillations related to eigenmodes excited primarily by wind flow and oscillations of the building structure have been observed. The long-term permanent monitoring of the 44-store building in Moscow allowed to observe the creep of the concrete properties (the eigenmode frequencies changed by 20%) and seasonal variation (about 2% changes over a year).*

1 INTRODUCTION

The study of the eigenmodes of high-rise buildings has two main aspects: practical and scientific. The practical aspect consists of the possibility to estimate the condition of the building as a whole or to monitor the load-bearing constructions. The monitoring of the eigenmodes is technologically and cost-effective solution to control the changes of the principal load-bearing construction in real time. Indeed, the eigenmodes excited by wind or microseisms exist permanently, and using of high sensitive seismometers and modern digital data acquisition systems makes it possible to define the oscillations frequencies with practically any prescribed accuracy. On the other hand, the changes in load-bearing constructions properties or in “fixing” of the building on the ground manifest themselves in the changes of natural frequencies. Thus, we have a very sensitive instrument of monitoring. Moreover, only few observation points with the sensors installed are required, and in some cases it is possible to install the sensors on the ground in the vicinity of the building under study.

The scientific aspect consists of the fact that using the monitoring of the eigenmodes of a building it is possible to observe the processes in constructions in real scale — not on the models or construction fragments. As it’s shown below, one succeeds in detecting the concrete creep effects, temperature changes, and to prove the correctness of theoretical conceptions on the constructions operation by means of comparison of the parameters obtained by calculating models and real measurements. Another important scientific aspect concerns the fact that the high-rise buildings are parts of artificial relief and are able to contribute some variations into the complex atmosphere-lithosphere interaction system. From some manifestations of this it is possible to obtain a practical result — using of the eigenmodes of high-rise buildings as instruments of our planet study; we’ll illustrate that fact below using experimental examples.

2 THE INSTRUMETATION AND METHODOLOGY OF OBSERVATION

In Russia the study of high-rise buildings oscillations induced by the effects of the wind pulsations began in 1950s by works of I.L. Korchinsky on several objects in Moscow [1], particularly on the main building of the Moscow State University (fig.1). The central 33-flour part of the building is detached from it’s ells by movement joints and has steel load-bearing constructions, while the base of the building is the frozen ground. The feature of the building maintenance is that it has not been reconstructed for more than 50 years and the area in radius of several hundred meters has not been built on, that is the ground conditions have not being changed. From this point of view the building of the Moscow State University is unique and gives the possibility of the most pure observation of the effects of aging of the constructions. We reproduced the observations of I.L. Korchinsky 50 years later, exactly in the same points of the building; differences were only in the types of used seismometers and the way of data acquisition. The sensor created by Korchinsky did not allow to detect signals below 0.2 Hz, and the oscillographic detection technique defined the 0.05 Hz oscillation frequency measurement precision. Nowadays we have no such restrictions.

The registration of the building eigenmodes can be performed with both seismometers and deformometer, and seismometers are preferable at frequencies above 0.1 Hz. In seismometrical registration velocimeters or accelerometers are used, giving correspondingly velocity or acceleration of a point of the building. It is significant that the microseismic signals are being observed in a wide frequency range, and the following processing enhances the informative signals from this range. For that reason it is preferable to use velocimeters at lower stores of the tower building — here the long period motions is strong and observation technique is simpler.

Taking into account the fact that the eigenmodes of the high-rise buildings have distinct rotational component, it is rational to carry out the observations using both linear and rotational sensors. Surely, the rotational component declare itself in records of the linear sensors signals too, but to extract the rotational component in this case one should realize the special sensors disposal and its' exact synchronization that sometimes is not quite possible inside the building. In our experiments the 3-component (X, Y, Z) linear sensors were used: velocimeters models SM-3 (Russian standard sensor) and CMG-3TD, accelerometers model CMG-5T (Guralp ® Co.).

The direct registration of the rotational modes were carried out with the special sensors, installed side by side to the linear sensors and providing direct angular velocity data in XY, XZ and YZ planes. The rotational sensor model METR-03 produced by R-sensors, LLC were used in the measurements. The features of this sensor is that it uses liquid inertial mass and the high-sensitive molecular-electronic transducer, that convert the flow of the electrolyte solutions inside the sensor induced by small external angular motions due to seismic signals into electric voltage output in the frequency range from 0.03 Hz up to 100 Hz with the flat to angular velocity output. These sensors demonstrate very good prospects in a wide range of applications like seismic monitoring of high-rise buildings, bridges and other industrial constructions, vibration control of industrial and scientific equipment, oil and gas exploration geophysics, security systems based on seismic area control, etc. By now the practice has brought out clearly that such type of sensors is quite capable of recording at least small (M ~4) local earthquakes [7], and the rotational sensors are becoming more and more widely spread means of seismological investigations.

3 DATA PROCESSING

Taking into account that the values of the eigenmode frequencies are unknown a priori, the oscillations in each point were recorded in the broad band — from DC up to 30 Hz. Than, the standard procedures of the spectrum analysis with the power spectral density calculation (including fitting of the analysis window, smoothing and averaging) and following selection of the stably occurring in signal narrow-band spectrum peaks were applied. These peaks were considered as possible manifestation of the eigenmodes. Than, the induced oscillations and interferences were thrown off taking into account the following criteria [2]. The eigenmodes must meet the stated below requirement:

- presence in practically all points of the building (except the standing-wave nodes),
- amplitude domination at horizontal components; in case of elongate in plan building the frequencies of oscillation differ along different axes of the plan,
- the amplitude of the horizontal component of the first mode grows on the height of the observation point,
- as a rule, the value of the eigenmode frequency is not a multiple of 50 Hz, otherwise that is the vibration of the electrical engine,
- at simultaneous observation in two points of a building, the oscillations are to be coherent,
- at simultaneous observation of seismic oscillations and atmosphere pressure pulsation, the eigenmode amplitude spikes and the wind pulsations are to be correlated.

In case the sensors of the observation system were deployed in a large number of points , it is possible to use the algorithm of extraction of standing waves which the eigenmodes consist of, that is based on the estimation of the coherentness of the signal records in the points [3].

3.1 The main types and schemes of the observations.

The space-time registration systems. Monitoring of the building condition. Let's begin from the longest time period (50 years) for the Moscow State University main building (Fig.1). The combination of the observation points at the building was passed one after another, and for each point the peaks of the spectrum were marked out. The diagram on the Fig.1 shows the presence of the peaks (peaks repeatability) in the combination of the observation points for each frequency. From the diagram and presence of oscillations at certain points of the observation one can conclude that up to about 3 Hz peaks are characterizing the oscillations of the central part of the building cut by movement joints, range from 3 to 7 Hz corresponds to movement of the high-rise part of the building, and at upper frequencies — the oscillations of the spire and towers.

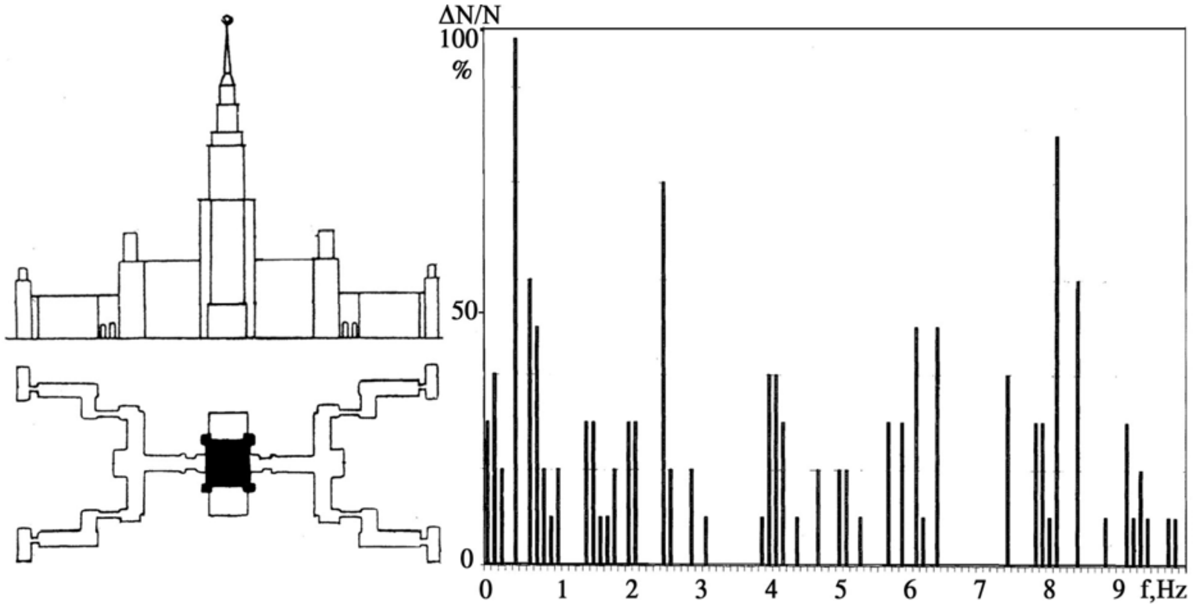

Figure. 1. Seismometrical diagnostic results for main building of Moscow State University: facade and plan to the left and peak reproducibility in spectra at observation points to the right.

Let's take another example — monitoring of the 44-storey apartment building "Edelweiss" in Moscow that was being carried out from very finishing of the constriction for about 8 years. The building is compact-size in plan (fig.2), monolithic ferroconcrete based on the complicated slab foundation construction. At the time of building construction finishing the frequencies f_1, f_2 of the 1st eigenmode were 0.73 and 0.54 Hz for different building axes. Than, the eigenmodes measuring were carried out with the 10 days time interval (chosen for weekly city activity dependence elimination [4]).

In fig. 2,b the time changes of the eigenmodes are shown. The trend is distinctly seen, that is "fast" during first 3 years and "slow" during next 3 years. The last year shows the tendency to speeding-up of the changes. The trend was extracted from the curves of the eigenfrequency time changes and low-pass filtration was made (fig. 2). At the curves for f_1, f_2 frequencies the annual rhythm is clearly seen. The presence of the annual variations is connected with the climatic-temperature influence at the reinforced-concrete building. The features of the time changes can be explained by the fact, that for the first 3 years only individual apartments were being heated, and that building was heated wholly, and the temperature inside the building was above 22 ºC in winter and decreases in summer. This has produced the time curves minimums in summer (the building is extended) for the first time interval, and later this refers to winter. Besides, during the first years the intensive apartment arrangement occurs increasing the loading of the building constructions, that gave rise the lowering of the eigenfrequencies and, partially, in difference in time curves for different eigenfrequencies. Another reason of the long-period eigenmode trend is the effect of the ferroconcrete creep that earlier was observed at samples, but now for the first time at real object.

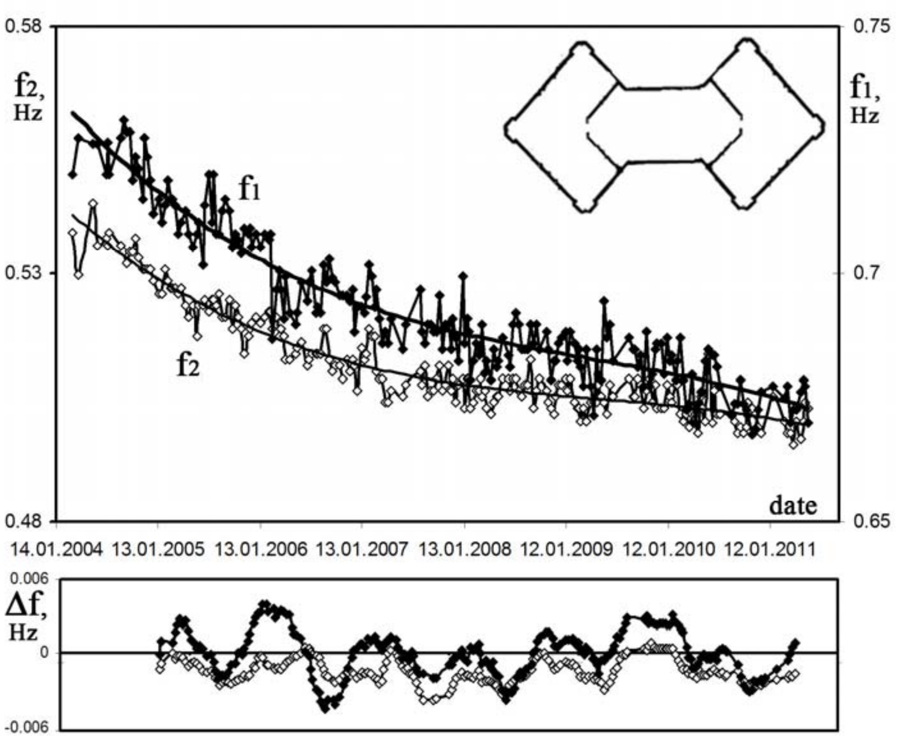

Figure. 2. The time changes of characteristic frequencies of a high-rise building: floor plan and time evolution with trend are shown in the upper part and results of low-pass filtration in the lower part of a figure.

It is significant, that the eigenfrequency drops about 20 percents relative to the initial value (or, about 2 % per year), and the annual variations are about 1 percent. Those are “natural” changes, and they are to be tacking into account when carrying out the monitoring of the building condition.

The interaction between different structures via ground is a well-known phenomenon for seismic interactions [5]. In a city environment the high-rise building are often situated at river banks and in neighborhood of bridges. Taking into account the close values of eigenfrequencies for such dissimilar constructions along with the simultaneous influence of the wind pulsations and big oscillations amplitudes of the bridges, we carried out some seismometrical observations on location.

The first example is the interaction of the 30-story building “Tower-2000” and “Bagration” bridge in Moscow-City complex. The constructions are closely adjacent but constructively untied. Their eigenmodes are different, for the 1-st mode the most intensive oscillations are detected at 0.58 and 0.98 Hz for Tower and bridge, correspondingly. Nevertheless, the Tower has the rather strong oscillations at 0.98 Hz, and on the top store the acceleration at this frequency exceeds the acceleration at eigenfrequency.

Another example refers to the construction interactions evaluation on the projecting stage of the high-rise building to be located in the vicinity of a bridge. The seismic observations made for the profile from the bridge to the site of the future building allowed to define signals going into the ground at eigenmode bridge oscillations and to select the most intensive modes and coincidence with the calculated eigenfrequencies. The real accelerogram obtained from the measurements was placed in the computational model, and the values of the displacements at dynamic impacts were received. The calculations showed that for the building located 200 meters from the bridge, the induced oscillations amplitudes (even in the case of resonance coincidence) are 103 times less then induced by the wind influence. This example shows the possibility of the seismometry on a projecting stage.

Observations of the rotational oscillations of the high-rise buildings. The analysis of the dynamics of the high-rise buildings calculation models shows that the eigenmodes set besides the “linear” oscillations has quite intensive rotational components. Fig.3 shows the pictures of the rotational movements based on the calculation model for the high-rise apartment building; the maximum displacement amplitudes due to the rotational oscillations 20-100 times less than due to linear ones. Thus at seismic measurements on the buildings, part of the spectrum peaks potentially reflects the rotational motions.

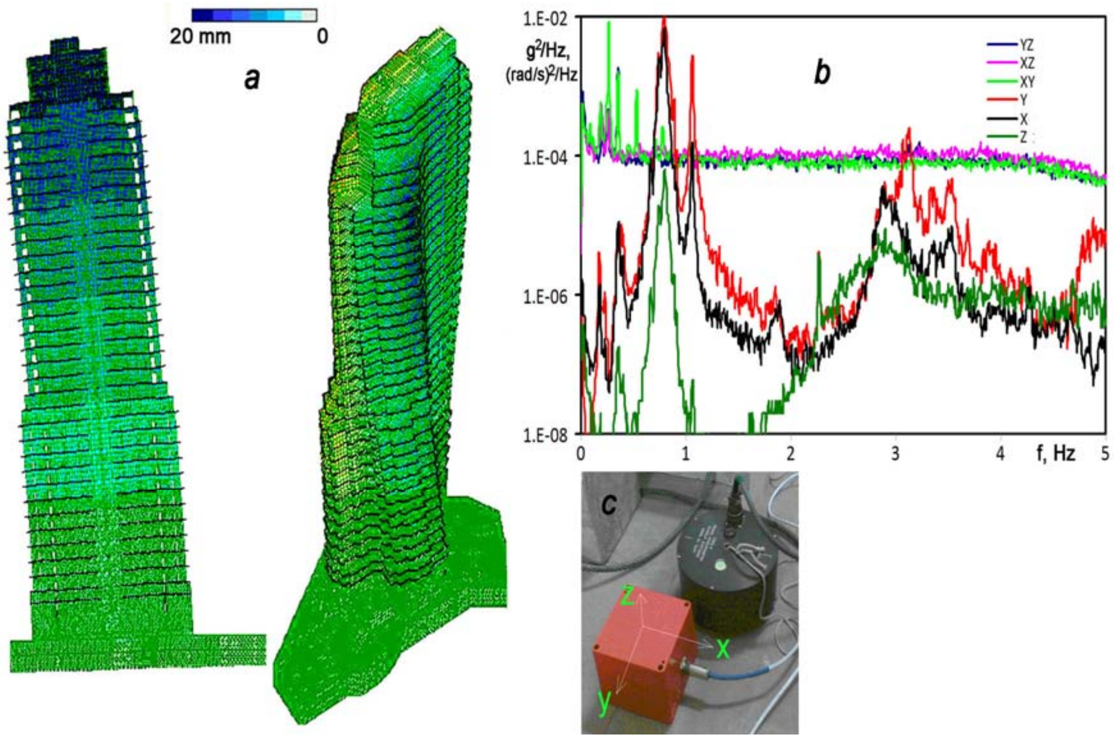

Figure.3. The study of high-rise building oscillations: a – calculations for linear (left) and rotational (right) vibrations, b – power spectra for both types of sensors. Photo shows the accelerometer Guralp CMG-5T and the angular velocimeter METR-03 (red) installed at the 38-th floor of the building under seismic monitoring

For clarifying of the matter the series of the experiments with simultaneous registration of the seismic signals at the building using both linear and rotational sensors were performed. The “linear” oscillations were recorded using the accelerometer and velocimeters by Guralp ®, and the rotational motions — by METR-03 sensors developed and produced by “R-sensors” LLC. In fig.3 the power spectrum densities for the records made with “linear” and rotational sensors are shown. The sensors were installed on the same base at the 38-th floor of the apartment building of simple shape. It is clearly seen, that the low-frequency spectrum peaks (lower than 0.5 Hz) correspond to the rotational oscillations. This fact is in good agreement with the results of the simulation. It should be mention, that the spectrums of the rotational records have the peaks due to the building motions only — at other frequencies almost only white noise exists, while the records of the “linear” sensors contains a lot of parasitic signals. This selectivity of the rotational sensors has good prospects for the monitoring systems operating in conditions of the high level industrial interference.

3.2 The computational and experimental data comparison for the building eigenmodes.

The calculations and measurements of the eigenmodes were carried during the construction when the height of the building was 8, 15, 22, 30, 37, 45 and 48 stories, and the obtained values of the eigenfrequencies were compared with each other. The following facts have been found:

– at relatively low number of stories (≤22) a lot of stably existing peaks is observed; the values of the observed characteristic frequencies coincide with the calculated frequencies just sometimes. This can be explained by the complicated volumetric-spatial composition of the building, especially at the lower part of the building. Besides, the backfilling of a part of the basement construction was not made by that time, that gave the more complicated fixing of the building in the ground then in the computational model; this played a important role in formation of the eigenmodes.

– the higher the building, the “simpler” integrally the building become in it’s shape; the number of spectrum peaks decreases and it’s values get to good agreement with the calculations. Nevertheless, there are some peak groups (for example, 0.6-0.7 Hz — the most intensive in the spectrum) that does not follow the calculation results. This proves the need for the building model improvement.

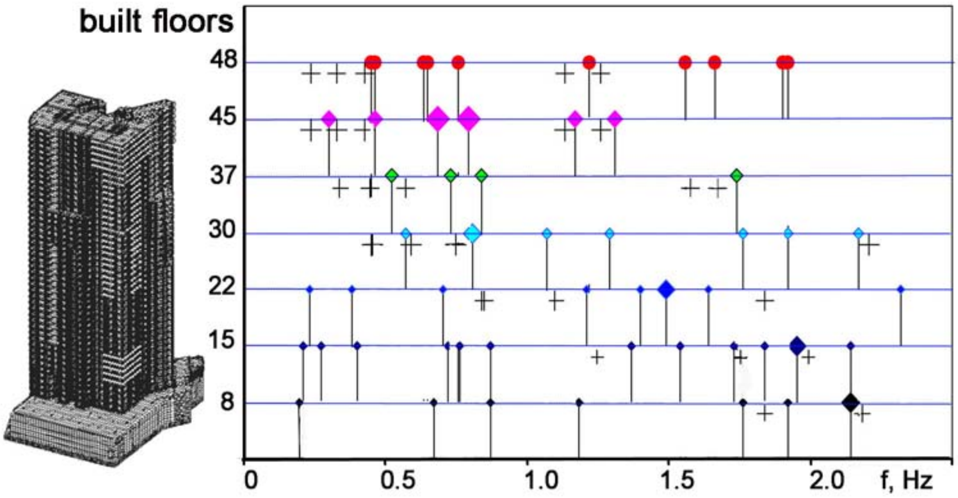

Figure 4. Eigenmode frequency change during construction of “Continental” high-rise building: crosses – calculated values, other correspond to experimental detection of persistent peaks in a microseisms spectra of the building.

3.3 The observations of the planetary phenomena on high-rise buildings.

As it shown above, at top stories of the buildings the eigenmodes amplitudes induced by wind pulsations are significantly greater than ones induced by microseisms via ground (including induction from the adjacent constructions). The simultaneous measurements of the pressure pulsations with microbarograph and mechanical oscillations clearly show the connection of these signals. The pressure variations are characterized by pulsations of different amplitude and time behavior. These signals modulate the amplitudes of the building eigenmodes. The long-term observations (for hours and days) of the eigenmodes amplitudes variations allow to reveal the modulating signal and to estimate it’s properties.

The fig.5 contains the result of the many-hours recording of the high-rise building “Tower-2000” eigenmodes — the Fourier spectrum of the envelopes for X-, Y- and Z-components of the seismic signal record. The series of peaks is clearly seen, and the most intensive peak corresponds to the 820-s period that coincides with an Earth eigenmode (free oscillation). The possibility of the appearance of the Earth eigenmodes in the atmosphere phenomena (including the detected frequency as one of the most powerful) were suggested earlier [6].

To verify this, the special experiment on the island Big Solovetskiy in the White See (a desolate island where the anthropogenic influence are minimal) was carried out. There is a steep mountain of 80 m height on the seashore with the lonely Ascension church on the top. The church height is 30 m, and the observations of the eigenmodes of the church were made on it’s upper part. So, relative to the surface the church in complex with the mountain is equivalent (in height and even in plan) to a high-rise building. The permanent measurements lasted for several days. In fig.5 the spectral-time diagram of the church eigenmode amplitudes envelopes is presented, that shows the presence of the series of the narrow peaks at the long-period part of the spectrum, particularly the 820-s peak. Besides, in fig.5 for the comparison with the obtained results, the diagram demonstrates the presence of the free oscillations of the Earth during “quiet” (without powerful earthquakes) time intervals. The result is obtained using the unique superconducting gravimeter [6]; the records were carried out in conditions of the weak man-caused interference in Arctic. Taking into account the significantly higher frequency resolution obtained [6] at long-term observations, there is a satisfactory agreement of the results. So, one may look forward to the high-rise buildings to be original instruments of the planetary investigations.

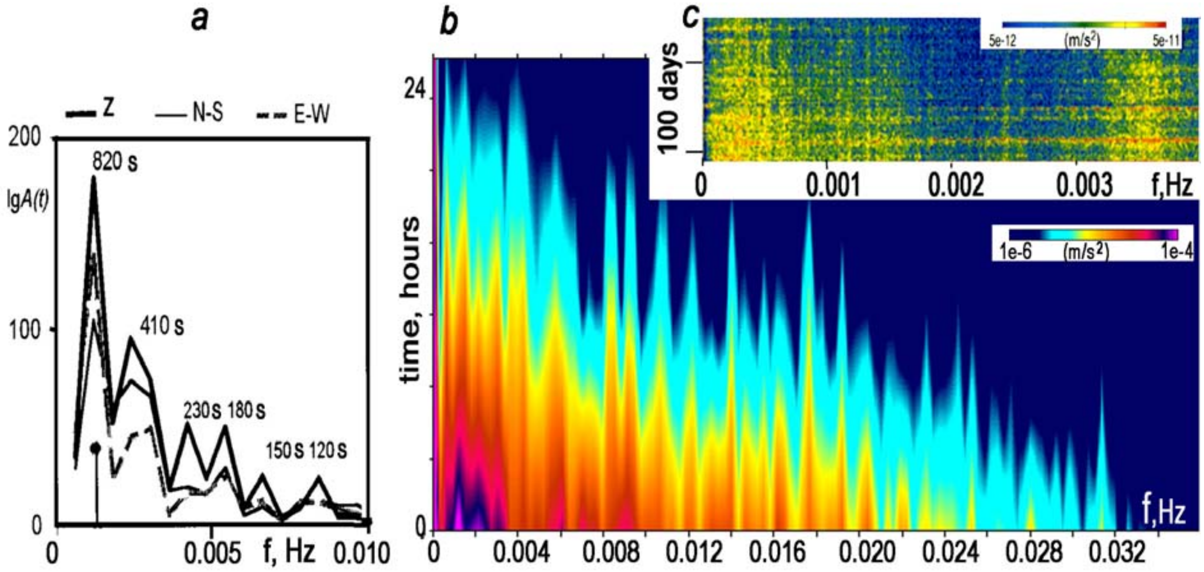

Figure 5. Earth characteristic oscillations observed as: a time variation of an envelope of high-rise buildings characteristic oscillations (power spectra (a) and time-spectral diagrams (b)) and a direct measurement by super-gravimeter [6] (c).

4 CONCLUSIONS

The following most important results has been obtained:

A portable monitoring system which includes a set of linear broadband motion sensors CMG3TD, CMG5T and unique highly sensitive, direct rotational readout, molecular-electronic sensors METR-03 has been designed and tested.

Both linear and rotational oscillations related to eigenmodes excited primarily by wind flow oscillations of the building structure have been observed.

Different allocation schemes of the sensors have been tested. It was found that most useful data can be obtained in case the sensors are located at some critical points which can be found a priory based on the numerical simulation of the structure response. The convenient and economical schemes for different types of buildings has been developed and tested.

The long-term (about 8 years) permanent monitoring during the course of construction of the 44-storey building in Moscow allowed to observe the long-term creep of the concrete properties (the natural frequencies were changed by 20% during the observation period) and seasonal variation of the elastic parameters of the building structure (about 2% changes in an year).

Based on the research results the following conclusions can be done:

The modeled and really observed parameters, especially for the lower eigenmodes, are very consistent for a simple or very high (>75 meters) buildings.

The well pronounced rotational oscillations of the building structures can be detected using either differential technique and traditional highly sensitive 3-component seismic sensors or special direct rotational-readout seismic sensors.

5 REFERENCES.

[1] I. L. Korchinsky. High-rise building oscillations (in Russian). *CNIISP Vol.11, Moscow*, p. 44, 1953.

[2] N. K. Kapustyan, E. A. Rogozhin. Soil properties and building dynamic studies by microseismic methods. *The International Conference on Modern Trends in Structural Engineering and Seismic Design*, Univ. Center of Samaria, Ariel, 8-11.10. 2007

[3] A. F. Emanov, V. S. Seleznev, A. P. Kuzmenko,S. A. Gritsenko,V. A. Saburov, I. A. Danilov, A. A. Bakh. Detailed engineering-seismological researches of buildings and structures. *Methods of study structures and monitoring of the lithosphere.* Novosibirsk, 142-153. 1998

[4] N.K. Kapustian The price of progress. *Science in Russia*, # 2, 15-23, 2000

[5] H.L. Wong, M.D. Trifunac Two-dimensional, antiplane, building-soil-building interaction for two or more buildings and for incident SH waves. *Bull. Seism. Soc. Am.*, **65,** # 6.1863-1885. 1975.

[6] K. Nawa, N. Suda, Y. T., FukaoSato, Y. Aoyama., K. Shibuya Incessant excitation of the Earth’s free oscillations. *Earth Planets Space*, *50*, 3-8, 1998.

[7] W.H.K. Lee, H. Igel, M.D. Trifunac, Recent Advances in Rotational Seismology, *Seismological Research Letters*, May/June, **80**, # 3, 479-490. 2009.