ГЕОФІЗИКА

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A NEW LASER APPROACH FOR SEISMIC RISK ASSESSMENT

(Представлено членом редакційної колегії д-ром геол. наук, проф. С.А. Вижвою)

In Europe, many countries have territories with the seismotectonic active areas – Italy, Greece, Romania etc. As we know, the special government and commercial organizations made many attempts to solve the seismic risk assessment problems in these countries using many different devices for solving these problems by estimating the seismic risk. All popular in all European countries specific devices are divided into two basic groups for solving the seismic risk assessment – accelerometers and velocimeters. For solving scientifically important tasks of the seismic risk assessment, there are no other high sensitivity devices for measurement of the displacements in countries with high level of the seismicity.

These problems are based on difficulty for business to produce effective devices for measuring the displacement. These problems are based on influences of the temperature on mechanical and electronics instabilities of systems for measurement of the displacement. The cost of devices for measurement of the displacement with temperature stabilization may be higher than for devices of measurement of velocity or acceleration. Broadband seismometers with very high exactness of measurements of seismic events of any type can be afforded by the countries with high financial achievements only. However, there are other more important problems for measurements of the displacement beside acceleration or velocity for any places where there are seismic active zones.

K e y w o r d s : ***laser devices, seismicity, risk assessment, hazard areas, building, statistical estimation.***

Background

For saving of any building in seismic dangerous areas in Europe the Global Seismic Hazard Assessment Program (GSHAP) was developed. It was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR) (United Nations International Decade …, n.d.). Fig. 1 shows the map of the Global Seismic Hazard Assessment since 1992.

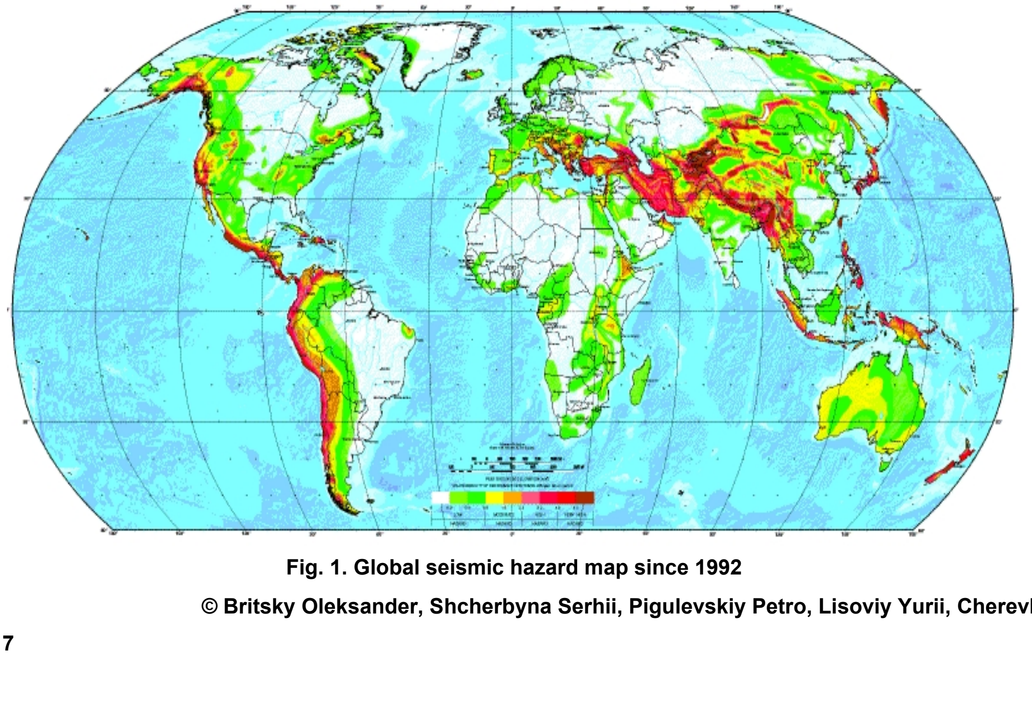

Fig. 1. Global seismic hazard map since 1992

This map was developed many years ago and the seismic intensity has significantly grown in all countries of Europe that are placed on seismotectonic active areas for the last five years. For example, fig. 2 shows a graph of seismic activity in Romania. All significant Romanian earthquakes with magnitude M > 5.0 happened within five years – from 2011 to 2015.

In the case of such growing seismic activity many new construction sites must be subjected to the processes of measurement of seismic waves and study of all properties of seismic intensity. For receiving of these significant results in Europe and other counties around it there are more popular devices as accelerometers and velocimeters (The Effectiveness …, n.d.). Only one calculated parameter as acceleration for estimations of all properties of seismic intensity is not enough for receiving all full results of seismic risk assessment. From physical point of view for estimating the properties of seismic hazard assessment for any building in dangerous seismic places there should be given three parameters as basic results – acceleration, velocity and displacement. For real evidence of significance of this difficult situation it is very important to remember dangerous event in China, where one high building was destroyed after dangerous technical preparatory works around it (http://truthfrequencyradio.com …) fig. 3.

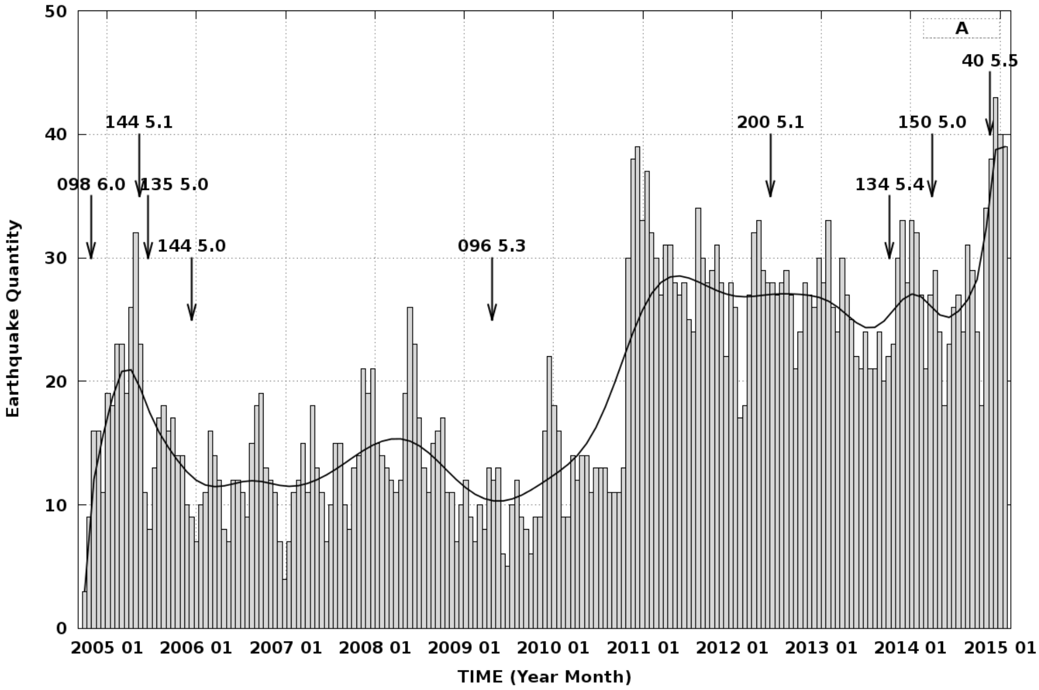

Fig. 2. The quantity of the earthquakes in Romania from 2005 to 2015 years

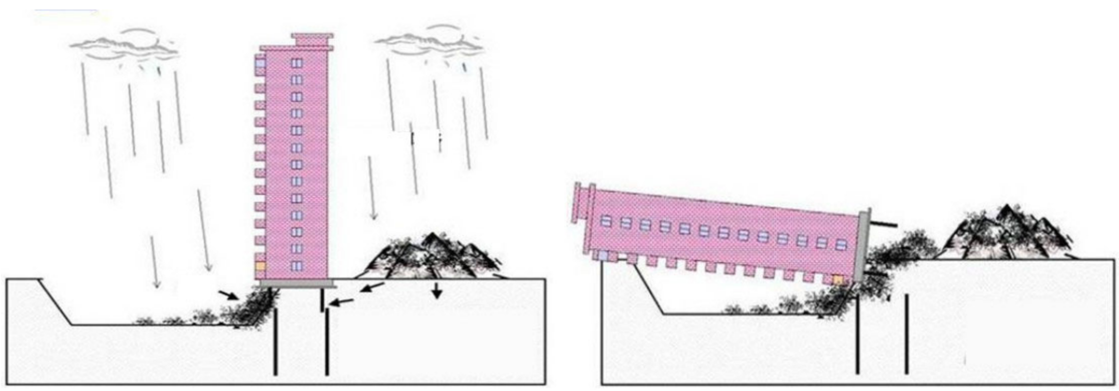

Fig. 3. Dangerous events with building in China with very low values of the frequency of their realization

In this case all the received values of accelerometers or velocimeters will be smaller by amplitude then amplitude of the displacement. It is the first problem with using of the acceleration or velocity only. Second problem is as results of numerical calculation velocity and displacement from acceleration (fig. 4). Fig. 4 shows a problem of the numerical computer calculation of the displacement from measured acceleration. As we see in fig. 4, the value of the displacement has 3000 millimeters as maximum and -1000 millimeters as minimum. Full amplitude of these calculated displacements will be 4000 millimeters or 4 meters. The cause of this significant error is a problem with traditional numerical calculations of different sums that are used for displacement calculation. For removing these difficult problems it is more suitable to use special devices for real measurements of the real displacements.

The new digital vertical laser seismometer and its properties. For realization of compact system for measurement of the displacement on different floors of the "Kyiv-Pechersk Bell Tower" the Mikelson's laser interferometer for measurement of the displacement was proposed to use. Note that the construction of laser interferometers may be different by approaches concerning the use of the mono-light optical systems for measurement of significantly limited displacements. Note that the design of the interferometer can be different. One of the options is shown in fig. 5. One from different variants is shown in fig. 5. In this proposed variant the principal scheme is based on the special scheme for generation and analyzing of optical information. The scheme of laser information processing is fundamental. This is the subject of the invention and distinguishes the proposed interferometer from the analogue (Yerazunis, Brinkman, 2009). Exactly this system is an item of invention and it has significant difference from analogue (Yerazunis, Brinkman, 2009).

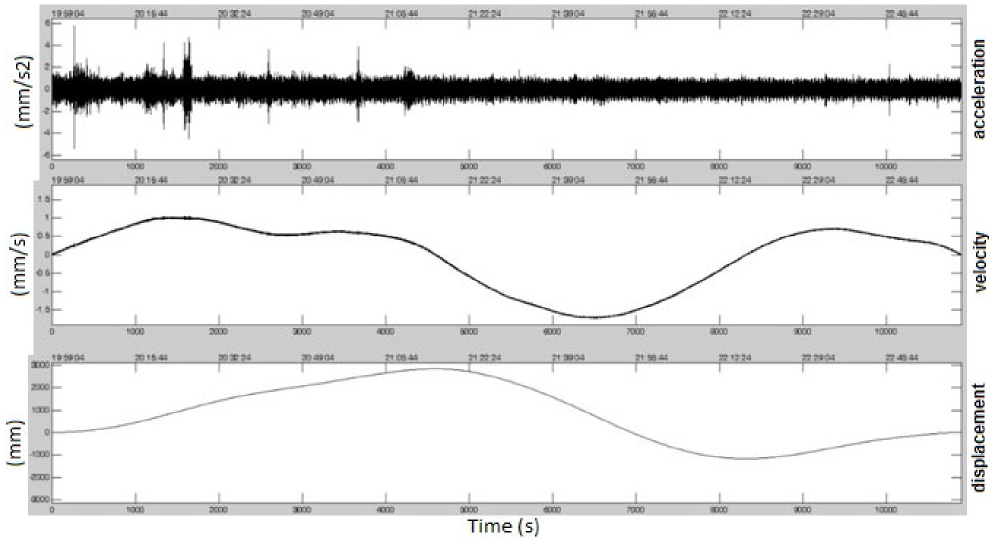

Fig. 4. Calculated velocity and displacement by real measured accelerations

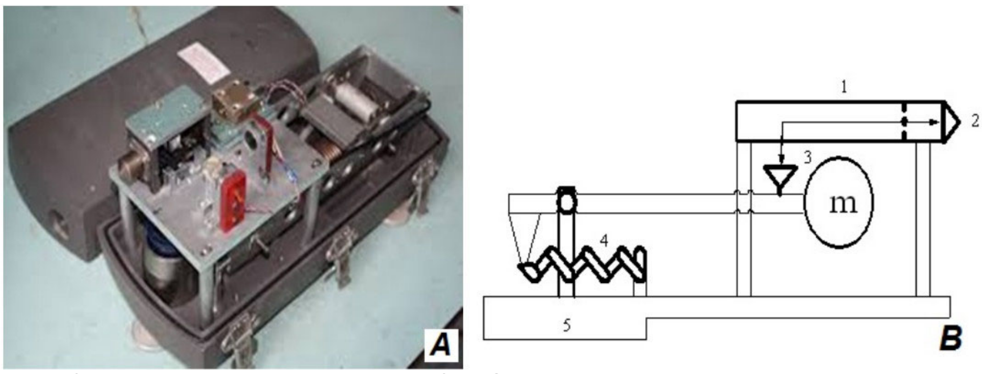

Fig. 5. Fragment of the equivalent mechanical circuit of the SL210 seismometer with built-in digital laser interferometer:
1 – body of the interferometer; 2, 3 – optical corner reflectors; 4 – pendulum suspension spring. *A* – SL210 seismometer; *B* – the lower part of the seismometer body, on which the main elements of its design are fixed (*Britsky et al., 2015*)

There is a variant of working with the main causes of displacement measurement errors by a compact semiconductor digital laser interferometer and ways to overcome them. It follows from the scheme of information processing of quadrature signals of the interferometer (fig. 5) that the relative displacement is defined as:

$$\Delta L_k = P * 2^B + X_k,$$

where: *P* – the number of segments λ/2 in the measured displacement; *B* – the bits depth of digitization of quadrature signals of the interferometer and elements of the correspondence matrix in fig. 5.

Thus, for example, at *B* = 9 the displacement in λ/2, regardless of the laser wavelength, is represented by the number 511. This means that in this case the real displacement will be represented as:

$$\Delta L_k = \frac{\Delta L_k}{511}\lambda/2,$$

where λ – is the length of the light wave in the space of the measurement.

Therefore, the main contribution to the measurement error of the relative displacement is made by the instability of the wavelength of the laser light in the measured space. The main reasons for this instability are as follows:

1. Influence of the temperature of a semiconductor laser on the wavelength of the light flux.

2. Influence of the parameters of the measurement medium on the wavelength of the light flux emitted by a semiconductor laser.

In addition, the relative displacement measurement error is affected by temperature changes in the dimensions of the measuring system structural elements.

Regarding the first factor, it can be argued that, firstly, the laser temperature must be kept within one mode, for example, in the proximity to one temperature T = 20ºC (fig. 6). In this case, roughly, the wavelength of laser optic waves will be 636 nm.

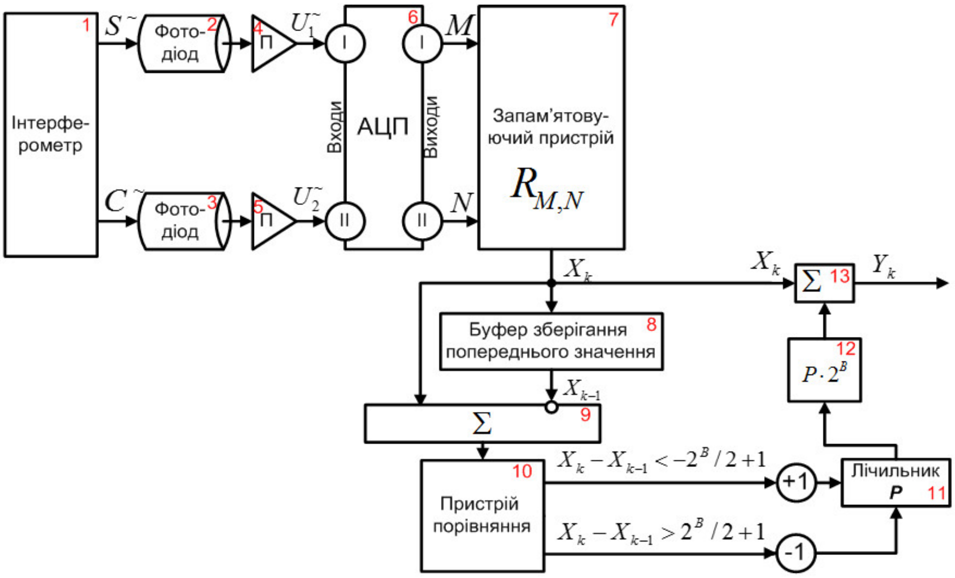

Fig. 6. Block diagram of information processing in a digital interferometer (Britsky et al., 2015)

However, within this mode, the relative instability of the generation frequency will have the next value:

$$\frac{\Delta f}{f_0} \approx \alpha \Delta T,$$

where α – is the coefficient of linear thermal expansion of the laser crystal (Gorelik, Lebedev, 2013). With regard to GaAs, we obtain 0,573*10^{-7} per 0,01ºC, which indicates the need for even more accurate stabilization of the crystal temperature.

It is difficult to take into account temperature changes in seismometer structural elements, since they are made of different materials. It seems simpler to stabilize the temperature of the instrument case as a whole. At the same time, from the point of view of technical implementation, it is preferable to heat the instrument case to a stable temperature, above the ambient temperature, rather than cooling to a certain temperature. From fig. 6 it follows that the chosen laser has stable and wide modes at temperatures, for example, 34ºC and 38ºC. Naturally, the ambient temperature will be lower or it will be possible to shield the device from direct sunlight. As final form, from preliminary investigations of the properties of the laser seismometer the advantages and disadvantages of using digital laser interferometers in seismological instruments are noted. The advantages include the following:

1. Extended low-frequency measurement range down to almost 0 Hz. This allows vertical seismometers to be used as delta gravimeters.

2. It has been experimentally proven that horizontal seismometers can be used as tiltmeters with a resolution of 10^{-4} rad. sec.

3. Open software allows to use digital laser interferometers not only for measurements, but also for control in closed systems.

The disadvantages include the need for precise stabilization of the temperature of the semiconductor laser, which complicates the operational using of seismometers. At the same time, theoretical and experimental studies have confirmed the possibility of a significant increase in the accuracy of temperature stabilization of a semiconductor laser by increasing the order of astatism of the temperature stabilization system to the second.

The results of our research have shown that digital laser interferometers can be used not only for measurements, but also when creating a broadband vibration platform for the purpose of metrological certification of geophysical instruments (fig. 7, 8).

The high accuracy of displacement measurement and open source software made it possible to create a broadband vibration platform for metrological certification of geophysical instruments. Fig. 7 has shown a fragment of the state metrological certification of the vibration platform itself using the linear measuring system ZL-80 (Renishaw), and fig. 8 shows an example of using a vibrating platform to obtain the frequency response of a vertical seismometer with a digital laser interferometer. The use of digital laser interferometers in seismometers made it possible to obtain new knowledge about geophysical processes in cultural and protected monuments of Ukraine.

The real displacement and calculated velocity and acceleration. "Kyiv-Pechersk Bell Tower" is a part of famous historic Orthodox Christian monastery what is registered in UNESCO (https://en.wikipedia.org/ …). Morphologically bell tower is located on the right bank of the Dnieper River outcrops within the plateau, which limited the valleys of the Dnieper and Lybid and cruciform ravine. The height of the plateau at the point of the bell tower is 190 meters above sea level. East of the bell tower in the direction of the Dnieper River plateau breaks almost directly.

"Kyiv-Pechersk Bell Tower" as a building object has an individual set of dynamic parameters with its own characteristics, which change, in consequence of the properties and effects of the environment (microseismic background). Methodical measurement microseismic background action in time for the controlled object using a laser seismometer is able to present a number of diagnostic parameters, namely natural frequencies and forms of fluctuations object spectral data values vibration displacement, vibration velocity and vibration acceleration of individual points of the object, logarithmic decrement of oscillations etc. It is based on the measured parameters obtained for effective and fairly rapid diagnosis of global technical condition of the object and its basic elements (fig. 9a, b). Fig. 9a, b have presented the original external appearance of bell tower and its architectural design.

For processing of measurement of the displacement it is very important to do the fixing of the temperature of environment for analyzing of the influences external condition on behavior of laser devices. The values has presented in table 1 of the Celsius temperature by points of the measurements and values of altitude these areas in meters and arranged by time.

Fig. 10, 11 have presented the laser records of measured real displacement (top) and calculated from it velocity (middle) and acceleration (bottom) for different floors of the bell tower (0.00 meters and 12.56 meters, respectively).

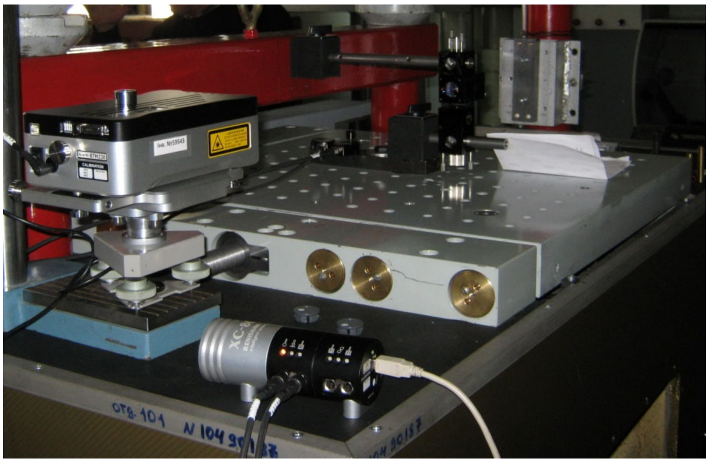

Fig. 7. General view of the main unit of the measuring system ZL-80

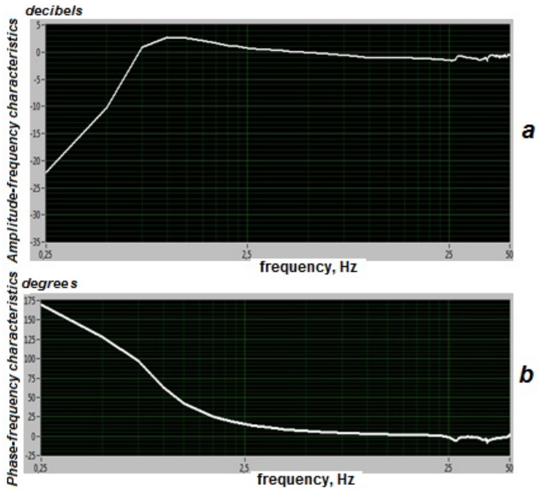

Fig. 8. Amplitude-frequency (*a*) and phase-frequency (*b*) characteristics of new vertical laser seismometer

Table 1

The Celsius temperature by points of the measurements

N floor (fig. 9b)	Date GMT +0 (d-m-y h:m:s)	Altitude (m)	Temperature (C)
1	29-10-2015 08:42:16	+00.00	no data
2	29-10-2015 09:57:11	+11.50	16.81
3	29-10-2015 10:58:58	+30.80	16.68
4	29-10-2015 11:38:34	+33.60	18.06
1a	29-10-2015 13:02:55	-05.00	10.68

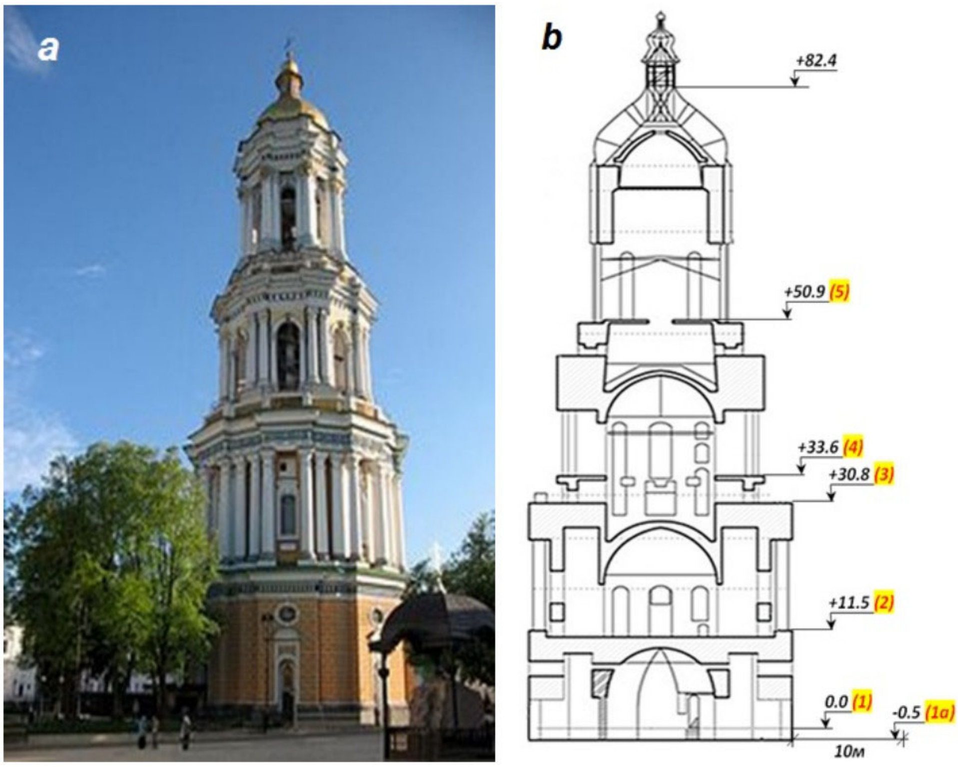

Fig. 9. The appearance (*a*) of the bell tower and its architecture construction (*b*)

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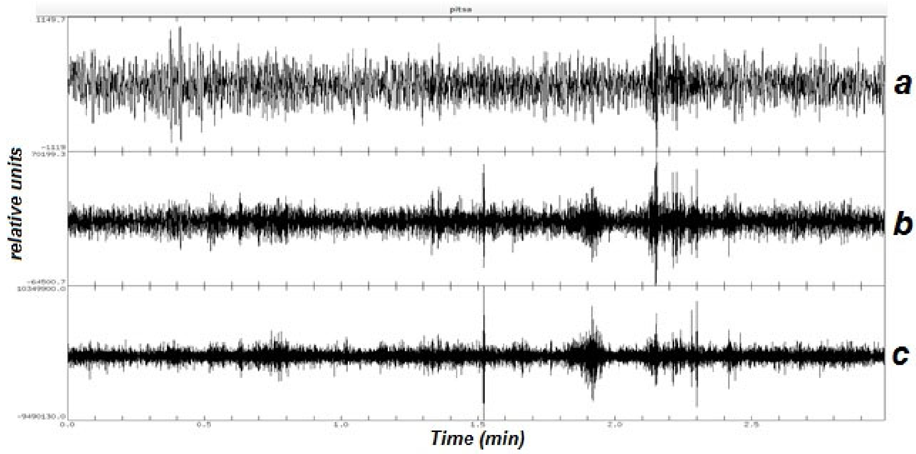

Fig. 10. The measured laser vertical displacement (*a*) and calculated from it velocity (*b*) and acceleration (*c*) in garden of the Lavra. The altitude of this point is equal 0.00 meters

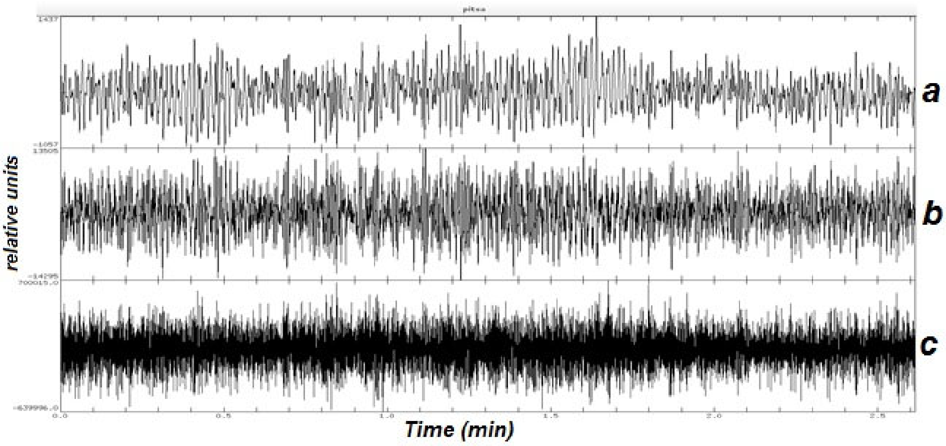

Fig. 11. The measured laser vertical displacement (*a*) and calculated from it velocity (*b*) and acceleration (*c*) for second floor "Kyiv-Pechersk Bell Tower". The altitude of this point is equal 12.56 meters

In the same figures we can see some short external influences that have external technical origins or sources and aren't own microseismic sources of bell tower that has a complicated architecture constructions.

The initial visual and short empirical analysis of all real measured and calculated records shows the availability of random behavior of it in time in case of changing by time of amplitudes all real and calculated records. For receiving of high quality estimates of the random properties of all real and calculated records there must be provided the results of some statistical estimations for receiving of reliable information about their properties. Because the seismic records have a random behavior in time for more effective investigation of this task the middle values of displacement must be calculated, velocity and acceleration for all temporal records, that were made on different floors of the bell tower.

For calculation of the middle values of the amplitudes microseismic record for vertical channel Z on different floors of bell tower (fig. 12) the arrays of real data of displacemen were used, calculated velocity and accelerations with quantity more than 10 000 counts, that were measured in nanometers units. The quantity of data more than 10 000 counts in arrays of laser data for different floors bell tower for calculation any statistical parameters is very important because low values of these values may lead to an insignificance of calculated results (table 2). This approach for comparison of significances between different kinds of measurements of microseismic vibrations displacement, velocity and acceleration is very important for successful building in seismic dangerous areas, because we found that the acceleration significantly exceeds (fig. 12) the values of displacement or velocity for all points that are distributed on different angles for different floors.

For calculation of the variance S of the displacement on different floors of "Kyiv-Pechersk Bell Tower" was used next formula, where X is array of values of displacement:

$$S^2 = \frac{\Sigma(X-\bar{X})^2}{\mathrm{N}-1}.$$

However, we should remember that the ordinary seismic events are not only ones that can destroy the building. As an example, man-made earthquakes may lead to dangerous situations, for example, as it happened in China with fully new building (http://truthfrequencyradio.com/…), fig. 3. For receiving successful results of measurements in defined area, we must select necessary type of basic devices that are more optimal for receiving effective results in areas of researching.

In fig. 4 we can see that the recalculation into new kind type of records may produce unexpected results with negative properties where the forms of calculated records of velocity and acceleration have spoiled numerical forms. Because the new developed laser seismic device that has been presented in this article is a first device, some statistical estimations of the properties for a measured and calculated microseismic records should be provided. The basic variants for this approach may be presented as two next methods:

a) spectral analysis of real laser records of the displacement and calculated from it velocity and acceleration and comparison of them with other real calibrated and sertificated geophysical devices, that were used in this area for measurements: accelerometer and velocimeter simultaneously (Кендзера, 2015). Some example of spectral researching of vertical laser microseismic records on different floors of "Kyiv-Pechersk Bell Tower" are presented in fig. 13. On third bottom parts of these FFT results for vertical laser we can see (a) some dominating frequencies that are based on architectural properties of this historical building.

b) special mathematical statistical estimation of real laser microseismic records that were made on different floors (1, 2, 3, 4, 1a) of "Kyiv-Pechersk Bell Tower" (fig. 9b) for determing the properties of randomly made seismic records.

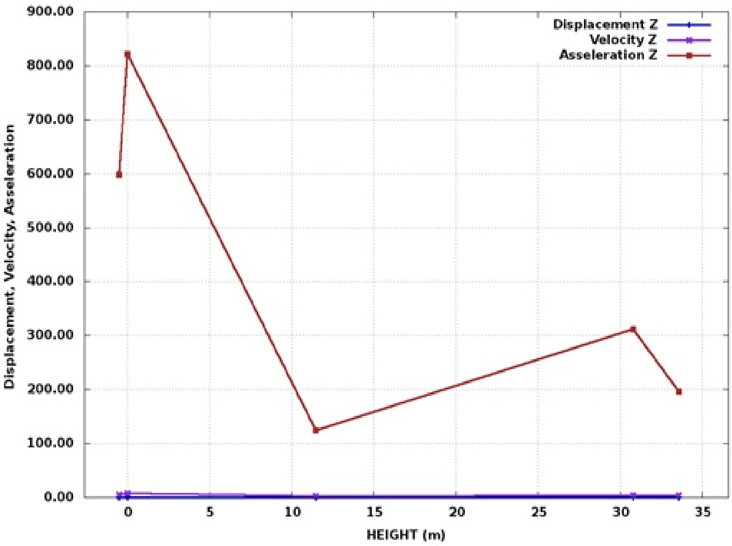

Fig. 12. First empirical statistical estimation of laser seismic records of various types as middle values of it for measured displacement and calculated velocity and acceleration

Table 2

Mean and variance values of measured laser displacements on different values of height

№	Height (m)	Mean (m)	Variance	Largest	Smallest
1	–0.5	1.79080e-07	1.90047e-14	1.14967e-06	2.14348e-11
2	+0.0	7.68555e-08	3.62683e-15	4.84445e-07	1.82450e-11
3	+11.5	2.82260e-07	4.73211e-14	1.43698e-06	2.29618e-11
4	+30.8	4.14021e-07	1.03988e-13	1.43698e-06	3.06668e-11
5	+33.6	3.38872e-07	6.66760e-14	1.60067e-06	2.60505e-11

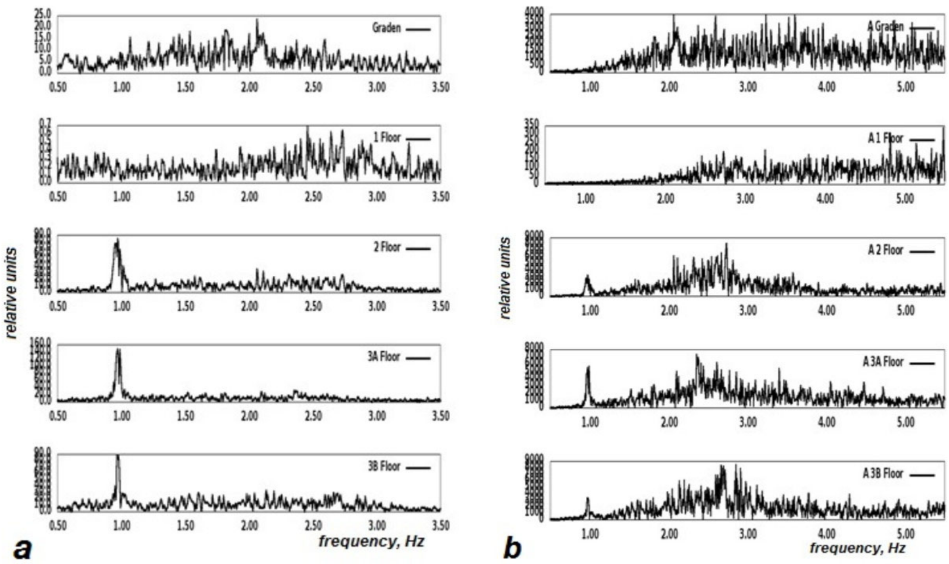

Fig. 13. The spectra of vertical laser measured displacement (*a*) and calculated acceleration (*b*) records on 1-3 floors of "Kyiv-Pechersk Bell Tower" and in garden.
On second and third floors have presented specific frequencies that all are equal about 1.0 Hz

As is known, the statistical temporal distribution of microseismic records in any area of Earth has the normal or Gaussian distribution (Maxwell, 2010), that is a very common continuous probability distribution. Normal distributions are important in statistics and are often used in the natural and social sciences to represent real-valued random variables which distributions are not known. In successful case of using of these methods for statistical estimation of laser records it is more suitable to have the experimental evidence that new developed interferometrical laser is a new device with important scientific properties that may be used in many technical or scientific areas for new approaches for receiving necessary information for seismic hazard assessment for places where there are the buildings in areas with dangerous geological cavities. (http://truthfrequencyradio.com/…). After application of several new numerical methods that were developed on base of using C software (*GNU Scientific Library, 2015*) and scientific software SCILAB with Opened GNU License (Urroz, n.d.) for calculation and receiving of necessary statistical parameters middle values of the displacement, velocity and acceleration (fig. 11) and calculated histograms (fig. 14) for measured and calculated values of the microseismic vibrations on all areas of measurements "Kyiv-Pechersk Bell Tower" were received.

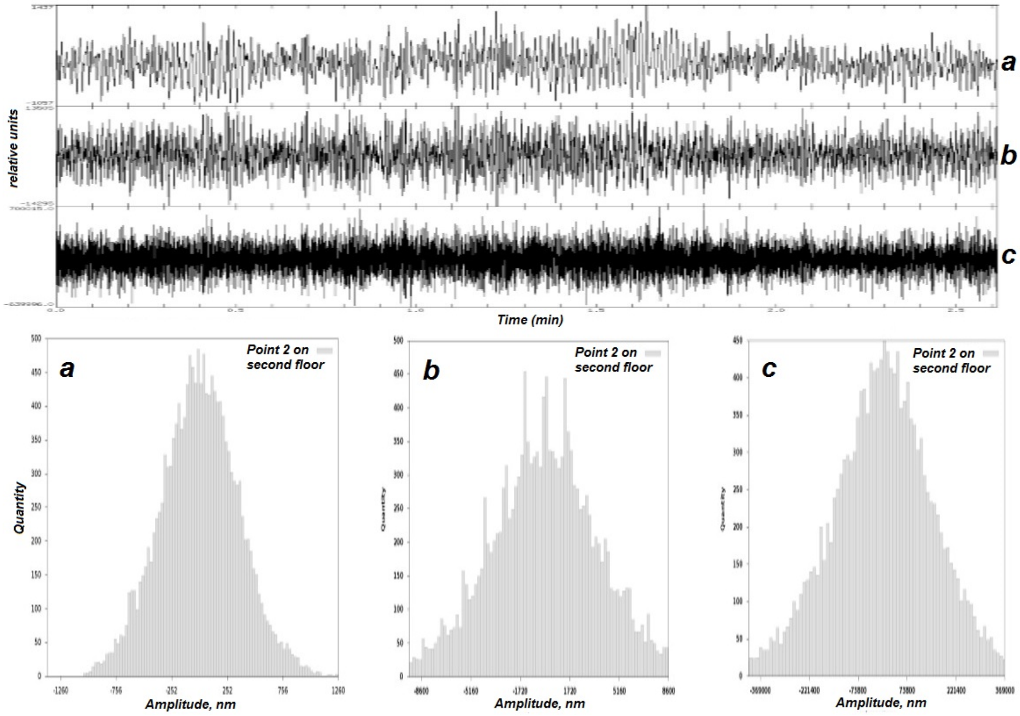

Fig. 14. The histograms for really measured displacement (*a*) and calculated velocity (*b*) and acceleration (*c*)

For higher exactness of evidence of existence of normal (or Gaussian) statistical distributions in time of all measured and calculated values of displacement, velocity and acceleration is more suitable to calculate the cumulative values of the probability for these measured or calculated numerical values. The results of cumulative probabilities of the values of measured displacement and calculated velocity have been presented in fig. 15. In fig. 15 of statistical estimations for measured displacement (fig. 15a) and calculated velocity (fig. 15b) and acceleration (fig. 15c) we see that they have a significant disturbances of it with different values for these calculated results.

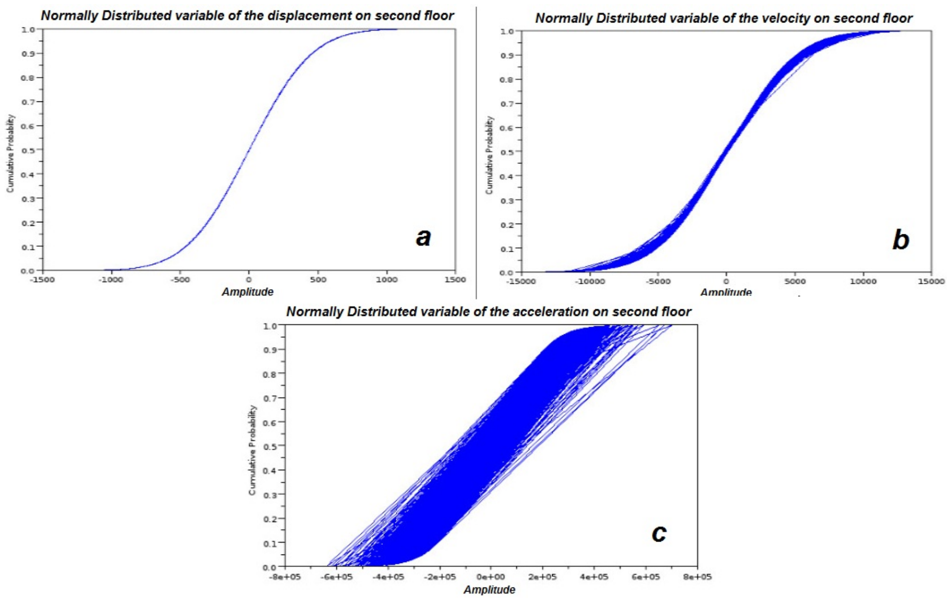

Fig. 15. Statistical estimation of measured displacement and calculated velocity and acceleration on second floor of "Kyiv-Pechersk Bell Tower" as cumulative probabilities of normal distribution of them:
a – for measured displacement; *b* – for calculated velocity; *c* – for calculated acceleration

Both these unexpected variances may be based on the limited possibilities of numerical calculations. If we look at fig. 13-a and 13-b we find the zones with randomity of amplitudes for these calculated FFT results on spectral graphs for accelerations. The chaos of amplitude in FFT transforms of calculated acceleration from originally regular signal of displacement may be based on insufficient intervals for digitizing of their values, because the acceleration must be calculated not on frequency 100 Hz but more, and it must be no less than in case of digitization of basic signal of displacement about 1000 Hz.

Conclusions

According to the results of our research, we obtained:

- an extended measurement range in the low-frequency region to almost 0 Hz, which allows using vertical seismometers as delta gravimeters;
- horizontal seismometers can be used as tiltmeters with a resolution of 10–4 rad.sec.;
- open software allows the use of digital laser interferometers not only for measurements, but also for control in closed systems;
- a broadband vibration platform for metrological certification of geophysical instruments was created;
- the staistical estimations all received data by different points had shown that the laser displacement has optimal possibilities to estimate seismic hazard assessment.

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НОВИЙ ЛАЗЕРНИЙ ПІДХІД ДЛЯ ОЦІНКИ СЕЙСМІЧНОГО РИЗИКУ

Багато країн в Європі мають території із сейсмотектонічно активними зонами – Італія, Греція, Румунія та інші. Як відомо, спеціальні урядові та комерційні організації робили багато спроб розв'язати проблеми оцінки сейсмічного ризику в цих країнах за допомогою використання великої кількості різних приладів. Всі популярні в європейських країнах спеціальні прилади для вирішення завдань оцінки сейсмічного ризику поділяються на дві основні групи: акселерометри та велосиметри. На сьогодні для вирішення науково важливих завдань оцінки сейсмічного ризику не існує інших високочутливих приладів для вимірювання рухів ґрунту.

Ці проблеми основані на труднощах ефективного виробництва пристроїв для вимірювання зміщень ґрунту. Недоліки цих приладів полягають у впливі температури на механічні та електронні компоненти систем вимірювання переміщення та їхню нестабільність. Вартість приладів для вимірювання зміщень ґрунту, які мають стабілізацію температури, може бути вищою, ніж для приладів, що вимірюють швидкість або прискорення. Широкосмугові сейсмометри з дуже високою точністю вимірювань сейсмічних подій будь-якого типу можуть дозволити собі мати й виробляти лише країни з розвинутою економікою. Також існує багато переваг для необхідності вимірювання зміщень ґрунту замість прискорення або швидкості для будь-яких місць, де наявні сейсмоактивні зони.

Ключові слова: ***лазерні пристрої, сейсмічність, оцінка ризику, небезпечні зони, будівництво, статистична оцінка.***

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