# Prospects of high-frequency gravimetry

Alexander L. Dmitriev

***Abstract*** - The gravitational field (GF) of the Earth is assumed to be a stochastic process the wide frequency spectrum of which is conditioned by the influence of various geophysical, astrophysical and anthropogenic factors. The frequency range of fluctuations of GF at frequencies over 1 *Hz* has not been significantly studied yet and still remains a peculiar "Terra Incognita" of gravimetry. Meanwhile, high-frequency changes of a free fall acceleration (FFA) data are informative for understanding of the complex physical processes happening in the core and crust of the Earth. They can be used to solve practical problems such as prediction of earthquakes, exploration of minerals, as well as problems of detection and identification of massive underwater or underground artifacts. Ballistic gravimeters with the test body executed in the form of a mechanical rotor with a horizontal axis of rotation should also be considered as perspective means of HF-gravimetry. Rotary motion corresponds to two oscillatory motions of the rotor particles along the orthogonal axis of coordinates. The accelerated harmonic motion of the rotor particles on a vertical is characterized by an infinite set of time derivates. In these condition the interaction of such rotor with a nonstationary gravitational field of Earth can have a specific, not trivial character. Such researches will promote obtaining the new data on dynamic characteristics and specific features of the gravitational field of the Earth.

***Keywords*** - ballistic gravimeters, free fall acceleration, gravitational field of the Earth, rotor

## I. INTRODUCTION

The gravitational field of the Earth is assumed to be a stochastic process the wide frequency spectrum of which is conditioned by the influence of various geophysical, astrophysical and anthropogenic factors. High sensitivity of the best modern gravimeters is achieved primarily through proper stabilization of temperature and mechanical characteristic of the equipment used and long integration time of registered signals – from tens of seconds to 24 hours [1]. Obviously, at large times of signal integration, the information about high-frequency variations of a gravitational field is lost. The frequency range of fluctuations $g_0(t)$ at frequencies over 1 *Hz* has not been significantly studied yet and still remains a peculiar "Terra Incognita" of gravimetry [2].

Meanwhile, high-frequency changes of a free fall acceleration (FFA) data are informative for understanding of the complex physical processes happening in the core and crust of the Earth. They can be used to solve practical problems such as prediction of earthquakes, exploration of minerals, as well as problems of detection and identification of massive underwater or underground artifacts.

High-frequency (HF) gravimetry data is of a great scientific and practical importance and the development of HF-gravimetry as a new research area is inevitable. Such gravimeters should provide an accurate measurement of the “instantaneous” value of FFA in the frequency range from few *Hz* to thousands (and probably more) *Hz*.

The most convenient modern tools of HF-gravimetry include superconducting gravimeters (SCG). Owing to a rather big proof mass, the highest frequency of variations in the gravity acceleration value registered by SCG does not exceed a few tens of *Hz*, although the frequency range of such measurements can be essentially extended after the improvement of these devices. Among HF-gravimetry measurement methods we should also mention the application of ballistic gravimeters with extremely small, less of 1 mm, length of the proof mass fall trajectory [3].

Ballistic gravimeters with the test body executed in the form of a mechanical rotor with a horizontal axis of rotation should also be considered as perspective means of HF-gravimetry.

Rotary motion corresponds to two oscillatory motions of the rotor particles along the orthogonal axis of coordinates. The accelerated harmonic motion of the rotor particles on a vertical is characterized by an infinite set of time derivates. In these condition the interaction of such rotor with a nonstationary gravitational field of Earth can have a specific, not trivial character.

## II. WEIGHT OF OSCILLATOR IN A VARIABLE FIELD OF GRAVITATION

Let's consider interaction of a mechanical rotor with an alternating gravitational field which is based on the gravitational analogy of the phenomenon of Faraday and Lenz's Law in electrodynamics [4-6]. According to [5,6] the change of acceleration of the gravity acting on a body, moving with acceleration $\vec{a}$ under influence of the elastic force, in the elementary (linear) approximation, is represented as

$$\Delta\vec{g}_{p,c} = -\frac{\vec{g}_0}{|\vec{g}_0|}(\vec{g}_0 \cdot \vec{a})A_{p,c} \qquad (1)$$

where symbols $p,c$ mean passing ($p$) and a contrary ($c$), in relation to a direction of vector $\vec{g}_0$ of normal acceleration of a gravity, orientation of a

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vertical projection of vector $\vec{a}$ of acceleration of external forces, and factors $A_p$ and $A_c$ characterize a degree of change of values $\Delta\vec{g}_{p,c}$. If the massive body under action of the external, electromagnetic in nature, elastic force makes harmonious oscillations along a vertical with frequency $\omega$ and amplitude $B$, the average for the period $\tau = 2\pi/\omega$ of fluctuations value $\Delta\vec{g}$ of change of FFA of such mechanical oscillator is equal to the sum of average changes of FFA in movement of a body passing and contrary to vector $\vec{g}_0$,

$$\Delta\vec{g} = \Delta\vec{g}_p + \Delta\vec{g}_c \qquad (2)$$

and at constant $g_0 = |\vec{g}_0|$ it is equal

$$\Delta\vec{g} = -\frac{g_0 B\omega^2}{\pi}(A_p - A_c). \qquad (3)$$

We shall present elementary time dependence $g_0(t)$ as

$$g_0(t) = g_0(1 + \beta\sin(\Omega t + \theta)) \quad , \qquad (4)$$

where $\Omega$ – frequency of changes of FFA value, $\beta$ - their relative amplitude, $\theta$ - the phase. Acceleration $a(t)$ of the material point making harmonious oscillations along a vertical with amplitude $B$ is equal to

$$a(t) = B\omega^2 \sin\omega t \qquad (5)$$

where $\omega$ - frequency of oscillations.

The averages for oscillation half-cycle $\tau/2$ of values of changes of accelerations $\Delta\vec{g}_p$ and $\Delta\vec{g}_c$ are equal to

$$\Delta\vec{g}_p = -A_p g_0 B\omega^2 \frac{2}{\tau}\int_0^{\tau/2}\sin\omega t(1 + \beta\sin(\Omega t + \theta))dt \quad , \qquad (6)$$

$$\Delta\vec{g}_c = -A_c g_0 B\omega^2 \frac{2}{\tau}\int_{\tau/2}^{\tau}\sin\omega t(1 + \beta\sin(\Omega t + \theta))dt \quad . \qquad (7)$$

The relative change of FFA of the oscillator, in view of 2, shall be presented as

$$\frac{\Delta\vec{g}}{g_0} = 4\pi A_p B F^2 f(x) \qquad (8)$$

where $F = \Omega/2\pi$, $x = \omega/\Omega$ and frequency function $f(x)$ is equal to

$$f(x) = -x^2\left[\int_0^{\pi}\sin z(1 + \beta\sin(xz + \theta))dz + \mu\int_{\pi}^{2\pi}\sin z(1 + \beta\sin(xz + \theta))dz\right] \qquad (9)$$

here $\mu = A_c/A_p$ and $z = \omega t$.

Examples of frequency functions $f(x, \mu, \theta, \beta)$ at various parameters $\mu, \theta, \beta$, and both low values of $x$ are shown in Fig. 1.

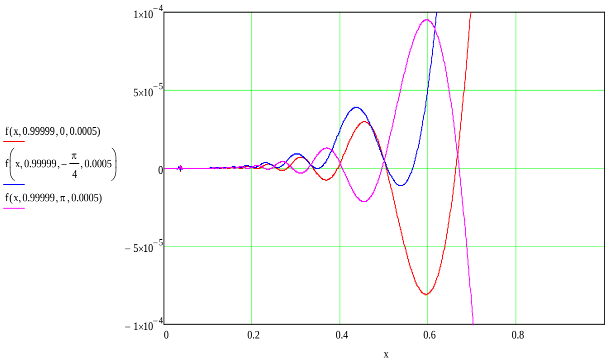


Fig. 1. Frequency functions $f(x, \mu, \theta, \beta)$ at low values of argument $x$; relative amplitude of fluctuations FFA $\beta = 0.0005$.

Obviously, the sign and a general view of functions $f(x)$ essentially depend on parameters $\mu, \theta, \beta$. According to estimations [4,5], in the calculations, $\mu = 0.99999$ is assumed. The given calculated dependences show that even at small, for example, with relative value of about the 100-th fractions of percent, amplitudes $\beta$ of fluctuations in value of normal acceleration of the gravity of the Earth, the weight of mechanical oscillator can be changed appreciably.

At frequencies $\omega$ of oscillations, with an order of the frequency $\Omega$ of own fluctuations of FFA, in area $x \le 1$, the weight of oscillator is periodically changes with frequency, with sign and values of such changes essentially depending on a difference of phases $\theta$ of oscillations and FFA (Fig. 1).

## III. Experimental Frequency Dependence of Free Falling Acceleration of Rotor

In our experiment the free falling acceleration of the magnetically-, thermally- and sound-isolated container with a vacuumed aviation rotor inside it was measured [7]. Appearance of a rotor is shown in Fig. 2.

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Fig. 2. Rotor

The maximal rotation frequency of a rotor is 400 *Hz*, the run out time of rotor is 22 min. Fall path length of the container is 30 mm, readout time of sample value of gravity acceleration is near 40 ms, the period of sampling is from 0.5 up to 1.0 minutes. The principle of measurements is based on photoregistration of movement of the scale in form of three horizontal strings fixed on the container. At the maximal falling velocity of the container equal to 60 cm/s and its dimensions of 82x82x66 mm, the joint influence of buoyancy and resistance force of air in FFA measurements did not exceed 0.1 cm/s$^2$. The error of some measurements of the container FFA was within the limits of 0.3-0.6 cm/s$^2$ and was basically determined by accuracy of readout times of registration of pulse signals in movement of the scale (near 1 microsecond).

The example of experimental frequency dependence of FFA changes $\Delta g(f)$ of the container, containing a rotor with a horizontal rotation axis, is shown in the Fig. 2.

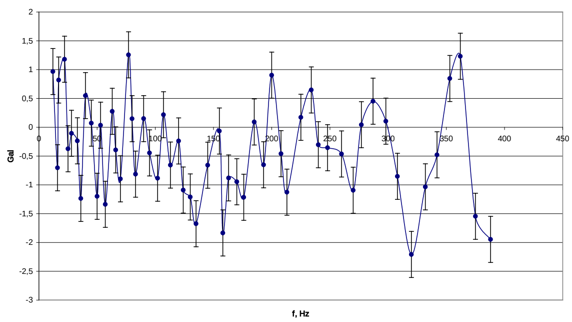


Fig.3. The frequency dependence of free falling acceleration of the container with horizontally positioned rotor; the changes of FFA ($Gal$) relatively to the value of FFA with the stopped rotor have been shown.

The value $\Delta g(0) = 0$ corresponds to acceleration of free falling of the container with a motionless rotor; FFA measurements of the container with a motionless rotor were carried out till the moment when rotor got going and after its run out time, in so doing the FFA values of the container, averaged by results of 10 measurements with a motionless rotor, coincided to the accuracy of 0.05%.

Comparing Fig. 1 and Fig. 3, it can be seen that the area of steady periodic changes of FFA in Fig. 3 in a band of frequencies 200-400 $Hz$ approximately corresponds to the area in a vicinity of value $x \approx 0.5$ in Fig. 1. Having substituted in 8 the experimental value $\Delta g / g_0 \sim 10^{-3}$, assume $A_p \sim 10^{-2} g_0^{-1}$, $f(x) \sim 10^{-5}$, we obtained an estimation of amplitude $B \sim 1.4\text{cm}$ of oscillator. The given size almost coincides with radius of the rotor used in experiments. At oscillation frequencies tens times higher than the frequencies $F$ of own fluctuations of normal acceleration of the gravity (according to the given estimations, $F \sim 300/0.5 = 600 Hz$) and following the suggested model, there is observed a monotonous frequency dependence of change $\Delta\bar{g}$ of average value of acceleration of free falling oscillator, with sign $\Delta\bar{g}$ beingis directly determined by the difference of phases $\theta$ of fluctuations FFA and oscillator. Within the limits of applicability of formulas 1,5 there are possible both substantial growth and reduction of the average gravity working on mechanical oscillator on the part of the variable gravitational field of the Earth. Let's note that the independent measurements of high-frequency, in the range of hundreds – thousands of $Hz$, spectra of fluctuations of acceleration of the gravity of the Earth, executed, for example, with use of SCG, will allow to define modes of the matched fluctuations of oscillator at which the changes of its average weight can essentially surpass the ones described by formulas 4-8.

## IV. Conclusion

The calculated and experimental estimations given above have an illustrative character.

Nevertheless, the considered simple phenomenological model finely explains the experimental dependences and agrees with the known data of measurements of weight of accelerated moving test bodies. Experimental researches into free falling mechanical oscillators (rotors, vibrators) will allow to bring the necessary specifications into the offered models, to determine the borders of their applicability, and to prove more strictly the size parameters introduced into these models. Such researches will promote obtaining the new data on dynamic characteristics and specific features of the gravitational field of the Earth. Development of HF-gravimetry techniques and exploration of above-mentioned "Terra Incognita" carries significant scientific and applied value.

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**Prof. Alexander L. Dmitriev** was born in Moscow in 1943. In 1967 he graduated from Dept. of Physics of Leningrad State University. For many years he worked in research and read lectures in the field of physical optics, sensors and lasers. Since 1993 he is a professor at St. Petersburg National Research University of Information Technologies, Mechanics and Optics. Beginning early 90ties, in cooperation with Institute of Metrology was engaged in research of precise weighing. He published more than 100 scientific works include of monographs “Controllable Gravitation”, published in Moscow in 2005, and “Experimental Gravitation”, published in St.-Petersburg in 2014 (in Russian). His main line of research is analogy of optical and gravitational phenomena and experimental gravitation.