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Simulation of the influence of parameters of disturbing vibration accelerations on the operation of a new two-channel transformer gravimeter

A new two-channel transformer gravimeter of an automated aviation gravimetric system was considered, the accuracy of which is higher than gravimeters known today. Its design was described. The influence of the parameters of disturbing vibrational accelerations on the operation of a new two-channel transformer gravimeter was simulated. The influence of frequencies and amplitudes of perturbing accelerations for the most unfavorable resonant cases on the operation of a two-channel transformer gravimeter was studied using a computer. After all, today there are no scientific, theoretical and practical works devoted to researching the possibility and expediency of using a two-channel transformer gravimeter as an AGS gravimeter. The transformer gravimeter contains a sensitive element consisting of a magnetic circuit, a movable armature, a primary excitation winding and a secondary output winding having two identical sections. Two sections of the secondary winding are connected in series-opposite, and the movable armature is connected to the motor, which, with a certain period, lowers the armature down and lifts it up along the magnetic circuit, and the motor is controlled by a switching device connected to the control voltage source, and the output signal from the secondary output winding is fed to the input of the output signal calculator, where an output signal is generated that is proportional to twice the value of the gravitational acceleration. A transformer gravimeter is a means of measuring the vertical component of the gravitational acceleration vector from an aircraft and can be used in the field of geodesy, geophysics, in particular, in the formation of reference gravimetric grids in hard-to-reach areas of the globe, as well as in aircraft and rocket building. The transformer gravimeter is part of the aviation gravimetric system placed on the aircraft.

Keywords: two-channel transformer gravimeter, disturbing action, resonant modes, damping, gravitational acceleration.

Introduction

Today, the use of an aviation gravimetric system (AGS) for mineral exploration (geology, geophysics, geodesy), for the correction of inertial navigation systems (aircraft and rocket science), for locating moving objects in the waters of the seas and oceans (military area), etc. Gravimetric measurements are made on the surface of the Earth, on submarines, on surface vessels and on aircraft. Airborne measurements make it possible to obtain information on gravitational acceleration (GA) in hard-to-reach areas of the globe with a speed and efficiency much higher than ground-based measurements.

Ground-based gravimetric systems do not allow determining GA in hard-to-reach regions of the Earth; they are carried out extremely slowly. Traditional airborne gravimetry is characterized by somewhat outdated technology and an insufficient level of accuracy. Aviation gravimetry has undeniable advantages over land and sea gravimetry. This is both greater speed, and the ability to carry out measurements in hard-to-reach areas of the Earth, higher productivity, and a fairly high measurement accuracy. It is possible to significantly improve the accuracy by using an aviation gravimetric system [1], the sensitive element of which is a new two-channel transformer gravimeter, the advantages of which over the known gravimeters are high accuracy, powerful output signal, linearity of the characteristic over a large range, etc.

Review of scientific literature on the research topic. The analysis of the literature has shown that a great contribution to the theory and practice of measuring transducers, which are the basis for the operation of gravimeters, is associated with the names of L. Bergman, G. Tiersten, A.A. Andreeva, V.V. Malova, N.A. Shulgi, V.V. Lavrinenko, S.I. Pugacheva, O.P. Kramarova, A.E. Kolesnikova, P.A. Gribovsky and others [1-10].

To date, there are several types of gravimeters for aviation gravimetric systems, which have both advantages and disadvantages. In [4], the elastic element and the moving mass are made in the form of an element made of a sapphire single crystal. The invention [5] improves accuracy by reducing zero drift, increasing the range of linearity, and improving the filtering of inertial noise. In the gravimeter [6], the sensitive element for determining the BC is made of silicon or glass. This provides the sensitive element with exceptional reliability, high accuracy and stability of readings with respect to time and temperature.

Leading technical universities in the USA, Japan, Germany and other countries of the world are developing new models of AGS gravimeters and improving their accuracy [11-14]. However, almost all known gravimeters simultaneously measure the useful signal GA and the noise signal of vertical acceleration [1, 9, 15], which is 10^3 times greater than the useful signal GA [1, 9]. They need long-term periodic calibration, tuning, filtering of the output signal [16], which greatly complicates the work. The existing latest developments relate to marine [17, 18] and land [19] measurement methods that are not used in aviation gravimetry.

In the last 20 years, mainly quartz heavily damped gravimeters, string gravimeters, and gyroscopic gravimeters have been used as aviation gravimeters [20–27]. A single-channel capacitive gravimeter (CG) is also known. It is the main sensitive element of automated AGS [28]. However, the single-channel CG does not provide for the elimination of errors caused by the influence of vertical acceleration, as well as instrumental errors.

It is known [29] that the capacitive method of mass displacement measurement provides high accuracy only when measured by its compensation method, in which the gap is kept constant. Provides an accuracy of 2 mGal, which is not sufficient for GA measurements.

In the invention [30], the elastic element and the moving mass are made in the form of an element made of a sapphire single crystal. This element has the shape of a polyhedral prism with two through side holes. However, the sensitivity of the gravimeter is limited mainly by aging processes and depends on the change in the elastic properties of the spring in the gravimeter with temperature.

The gravimeter [31] consists of a quartz sensitive system damped by a liquid. The invention improves accuracy by reducing zero drift and increasing the range of linearity. The disadvantages of this gravimeter is the complexity of the design, the lack of full compensation of the main interference – vertical inertial acceleration; the presence of a filter complicates the design and reduces its reliability.

According to analysts from Gartner, microelectromechanical systems make it possible to increase the sensitivity and accuracy of converters (sensors) at the crystal level at minimal cost. Capacitive, piezoelectric, tensoresistive, thermoresistive, Hall effect, photoelectric converters are mainly used. Capacitive MEMC accelerometers manufactured by AnalogDevices, Bosch, Delphi, Denso, Freescale, Kionix, SiliconDesigns, ST Microelectronics, VTI Technologies are leaders in the modern market [12]. However, the accuracy of their work and the stability of the characteristics are not high enough. They are unstable, depend on the influence of external electromagnetic fields, which are large on the aircraft.

Having studied and analyzed the literature and Internet data [20-31], we can conclude that the known gravimeters have the following main disadvantages: non-linearity of the initial characteristic; low measurement accuracy (2-8mGal); the need to use complex procedures for filtering the output signal of the AGS gravimeter using special filters; the presence of instrumental errors and errors from the action of vertical acceleration; low speed of information processing (processing of the results of gravimetric measurements is carried out on Earth for months) and others.

The proposed transformer gravimeter (TG) [7] has undeniable advantages over known gravimeters: it measures acceleration in both positive and negative directions. The TG can measure static accelerations and vibrations with high accuracy. The main part of the gravimeter is a symmetrical sensitive element (SE), which has two sensitive transformer converters [1]. This reduces temperature dependence, sensitivity to cross-accelerations and increases linearity. The influence of vertical acceleration is eliminated, as well as instrumental errors and errors from non-identical parameters of the two channels are eliminated. An increase in the power of the output signal of the TG is provided by feeding the output signals of two transformer converters to the adder, where the useful output signal GA is doubled.

Statement of the research problem. Today, there are no scientific-theoretical and practical works devoted to research of the possibility and expediency of using a two-channel transformer gravimeter as an AGS gravimeter, the advantages of which over known gravimeters are greater accuracy (due to the elimination of the effect of vertical acceleration, instrumental and other errors) and sensitivity, small weight and size characteristics , simplicity of design, and others [7]. Therefore, it is expedient to study the parameters and characteristics of this type of gravimeter.

The object of study of this article: the process of measuring the acceleration of gravity.

Subject of the article: two-channel transformer gravimeter.

The purpose of this article is to model and study the influence of the parameters of disturbing vibrational accelerations on the operation of a new two-channel transformer gravimeter (two-channel TG) of an automated aviation gravimetric system using a computer.

Objectives of the article: to present data on the design and principle of operation of a new two-channel transformer gravimeter; to investigate the stability of two-channel TG; to simulate the effect of disturbing vibrational accelerations on the operation of the two-channel TG; develop software and use it to investigate the influence of frequencies ω, amplitudes w_a, w_b of disturbing vibrational accelerations and damping coefficient for the most unfavorable resonant cases: $\omega = \omega_0$, $\omega = 2\omega_0$, $2\omega = \omega_0$; where ω_0 is the natural frequency of the two-channel TG; analyze the obtained simulation results.

Research methods and materials

Next, we present the main materials and research methods in accordance with the goals and objectives.

1. Stability studies of a system with a two-channel TG

When carrying out measurements, a transient process always occurs, in which the output signal of the measuring instrument changes significantly with time. This is explained by the inertial properties of the measuring instrument, which cause the appearance of a dynamic error [1, 8]. The system under study is nonlinear, like most systems in nature and technology. In [1, 9], the characteristic equation of the two-channel TG system was obtained:

$$D(p) = T^2 p^2 + 2 \cdot \xi \cdot T \cdot p + \left(1 + K_{TCTG}\right) = 100\, p^2 + 14\, p + (1 + 40). \tag{1}$$

With a stable two-channel TG system, under any real impact on it, the controlled value during the transient will not deviate from the set value indefinitely. There are many stability criteria, both analytical and graphical. The best known are the Nyquist and Hurwitz criteria. Let us define the stability of the system with two-channel TG according to these criteria. In accordance with the Hurwitz stability criterion, in order for the automatic control system to be stable, it is necessary and sufficient that all Hurwitz determinants have the same signs with the sign of the leading coefficient of the characteristic equation a_n, that is, when $a_{n-1} > 0$ they are positive [8].

Thus, a necessary and sufficient stability condition for a second-order system, which is equation (1), is the positivity of the coefficients of the characteristic equation. In our two-channel TG system, we observe the following:

$$\begin{gathered} a_0 = T^2 = 100 > 0, \\ a_1 = 2 \cdot \xi \cdot T = 14 > 0 \\ a_2 = 1 + K = 40 > 0. \end{gathered} \tag{2}$$

Thus, according to the Hurwitz stability criterion, the two-channel TG system (2) is stable.

Transfer function two-channel TG over the HA channel for the output voltage [8]:

$$W_{TG}(p) = \frac{K_{TG}}{T_1 p^2 + T_2 p + 1}, \tag{3}$$

where K_{TG} – static transmission factor two-channel TG, T_1 and T_2 – time constants of the object of the second order.

To study two-channel TG for stability, according to the Nyquist criterion, we use the two-channel TG transfer function (3):

$$W_{TCTG}(p)=\frac{40}{100p^2+14p+1}. \tag{4}$$

We substitute $p=j\omega$ into equation (4) and obtain the two-channel TG frequency transfer function:

$$W(j\omega)=\frac{40}{-100\omega^2+14j\omega+1}=\frac{40(1-100\omega^2+14j\omega)}{(1-100\omega^2)^2+j(-14\omega)^2}.=X(\omega)+jY(\omega), \tag{5}$$

where $X(\omega)$, $Y(\omega)$ – real and imaginary parts of the two-channel TG transmission frequency function, respectively.

We select from equation (5) the real and imaginary parts and find the point of intersection of the amplitude-phase characteristic (APC) real axis $X(\omega)$:

$$\begin{cases} X(\omega)=\dfrac{40(1-100\omega^2).}{(1-100\omega^2)^2+j(-14\omega)^2}; \\ Y(\omega)=\dfrac{40\cdot 14\omega}{(1-100\omega^2)^2+j(-14\omega)^2}; \end{cases} \tag{6}$$

$$X(0)=40.$$

Based on the calculated data (6), we construct the APC (Fig. 1) in the MatLab software environment (Nyquist hodograph).

In order for the two-channel TG system to be stable, it is necessary and sufficient that the Nyquist hodograph does not cover the point with coordinates (-1, j0). As we see from Figure 1, the point is not covered, therefore, the two-channel TG system is stable.

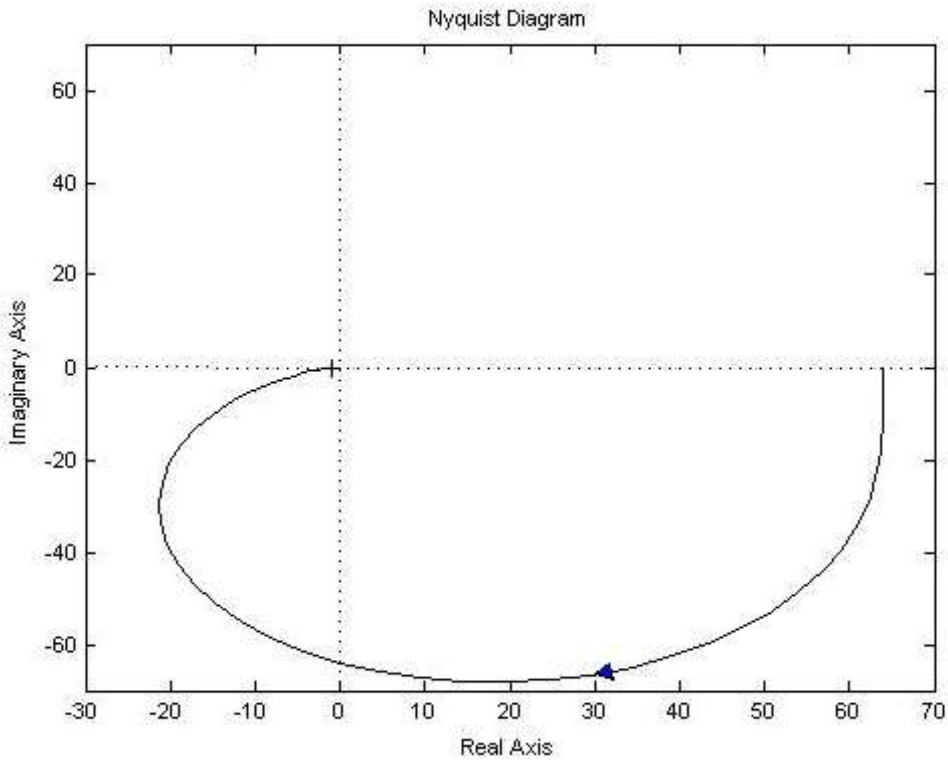

Figure 1. Amplitude-phase characteristic of two-channel TG

2. Design and principle of operation of the transformer gravimeter

The transformer gravimeter belongs to the means of measuring the vertical component of the HA vector on board the aircraft and can be used in the field of geodesy, geophysics, in particular, in the formation of reference gravimetric grids of hard-to-reach areas of the Earth, as well as in the aerospace area.

The closest analogue of two-channel TG is a solenoid-type *transformer converter* [1, 4] (Fig. 2).

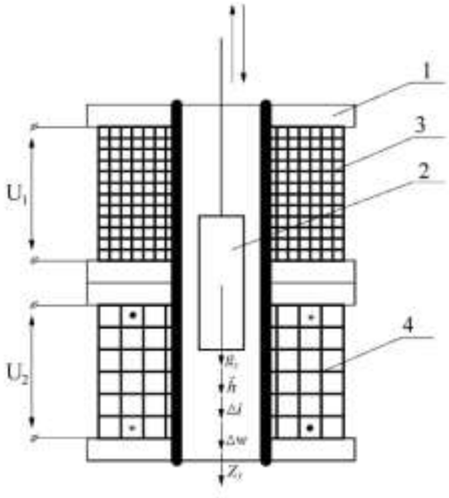

Figure 2. Transformer converter [1, 4]

The common essential features of a transformer converter (TC) and a transformer gravimeter (TG) is that they contain a sensitive element, which consists of a magnetic circuit 1, a movable armature 2, a primary excitation winding 3 and a secondary output winding 4, which has two identical sections.

However, unlike TG, TC has a number of disadvantages. Two sections of the secondary winding 4 W_2 in TC connected in series-accordingly (beginning-end of one section, beginning-end of another section). That is, the output winding 4 W_2 is solid (Fig. 2). Under the action of acceleration of the force of gravity g_z, which acts along the sensitivity axis of the transformer converter O_z, the force of gravity arises $G = mg_z$. Excitation winding 3 W_1 is connected to voltage U_1 and forms an electromagnetic flux of excitation Φ_1. According to the law of electromagnetic induction, this flux induces EMF E_2 in winding 4 W_2. Under the action of the acceleration of gravity, the anchor 2 moves down in the middle of the magnetic conductor 1 and causes a change in the electromagnetic flux Φ_1. Then the electromotive force E_2 in winding 4 W_2 will change in proportion to the acceleration of gravity $g_z : E_2 = mg_z$. The output electrical signal U_2 will be proportional to g_z: $U_2 = mg_z$. Under the action of an external electromagnetic flux of an obstacle (significant extraneous electromagnetic fluxes occur on moving objects: aircraft, surface and submarines), the EMF $E_П$ of the obstacle will be induced in the output winding 4 $W_2 : E_2 = mg_Z + E_n$. Accordingly, the output signal will be $U_2 = mg_Z + U_n$. Instrumental errors from the influence of changes in temperature, humidity, pressure, moment of dry friction forces, etc. are significant for TC and are not compensated in any way. Vertical acceleration $\ddot{h}$, when installing TC on aircraft, will act along the axis of sensitivity of the converter, then: $E_2 = mg_Z + m\ddot{h}$. The value of the vertical acceleration $\ddot{h}$ is 10^3 times greater than the value of g_z, that is, the value of the error significantly exceeds the useful signal.

Thus, a significant drawback of the TC is its low accuracy in measuring gravitational acceleration.

3. New two-channel transformer gravimeter

The new transformer gravimeter is based on the task of increasing the accuracy of measuring gravitational acceleration. *Transformer gravimeter* contains a sensitive element, which consists of a magnetic circuit 1, a movable armature 2, a primary excitation winding 3 and a secondary output winding 4, which has two identical sections. To improve the accuracy of measuring the gravitational acceleration, two sections of the secondary winding 4 are connected in series-opposite, the movable armature 2 is connected to the motor 5, which, with a certain period, sequentially lowers the armature 2 down and raises it up along the magnetic circuit 1, and the motor 5 is controlled by the switching device 6, which connected to the source 7 of the control voltage, and the output signal from the secondary output winding 4 is fed to the input of the device 8 for calculating the output signal, where an output signal is generated that is proportional to the double value of the gravitational acceleration (Fig. 3).

An increase in the accuracy of measuring gravitational acceleration in a new two-channel transformer gravimeter is provided as follows. Under the action of an external electromagnetic flow of an obstacle, this flow will induce two EMF obstacles in two sections W_2, which are included in series-opposite $E_{2\Pi}$ and $-E'_{2\Pi}$. In total, these errors are compensated. That is, such a counter connection of the sections provides compensation for errors from the influence of external electromagnetic flows, which can be significant when installing the gravimeter on a moving object. The action of instrumental errors from the influence of changes in temperature, humidity, pressure, moment of dry friction forces, etc. will be compensated in a similar way due to the counter connection of two sections W_2. Thus, the proposed transformer gravimeter provides a significant increase in the accuracy of measuring gravitational acceleration. *The essence of the operation of a two-channel transformer gravimeter (two-channel TG) is explained by the diagram in Figure 3.*

The sensitive element of the TG, as in the case of a transformer converter, consists of a magnetic circuit 1, a moving armature 2, a primary excitation winding 3 and a secondary output winding 4, which has two identical sections. Two sections of the secondary winding 4 are connected in series-opposite. The moving armature 2 is connected to the motor 5, which every second successively lowers the armature 2 down and up the magnetic circuit 1. The motor 5 is controlled by the switching device 6, which is connected to the source 7 of the control voltage. The output signal from the secondary output winding 4 is fed to the input of the device 8 for calculating the output signal, the output of which is a signal that is proportional to the double value of the gravitational acceleration and does not include errors from the influence of the vertical acceleration of the aircraft, residual instrumental errors, residual errors from the projections of horizontal cross accelerations and errors caused by the influence of external electromagnetic flows.

The new transformer gravimeter works as follows (Fig. 3).

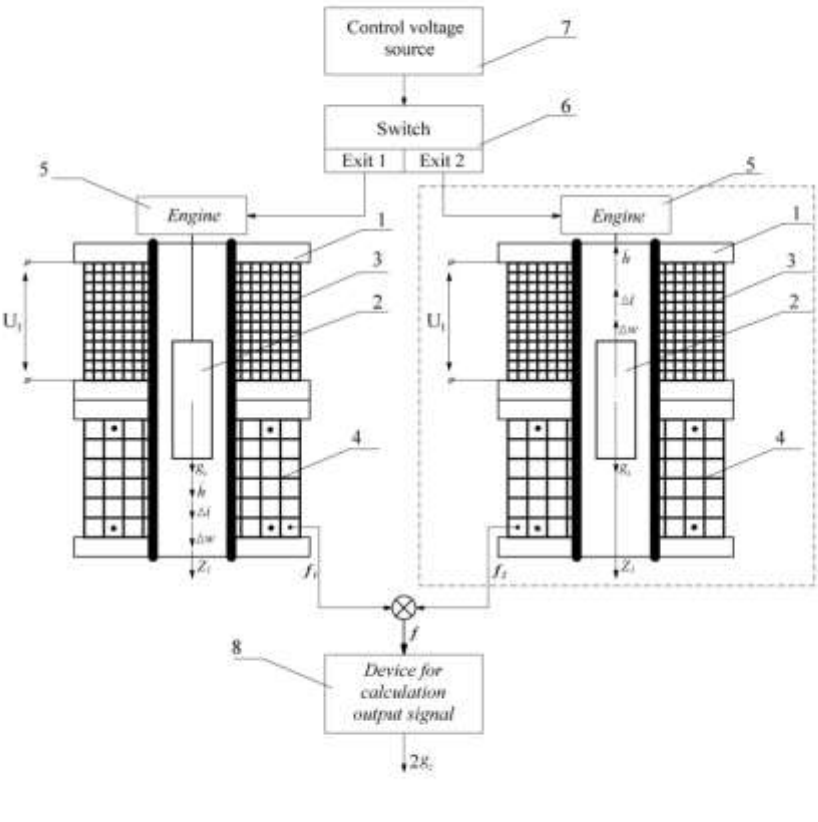

Figure 3. Block diagram of the new two-channel TG [7]

Under the influence of gravitational acceleration g_z, which acts along the sensitivity axis of the gravimeter O_z, there is a gravity force $G = mg_z$. The excitation winding W_1 is connected to the voltage source 7 U and creates an electromagnetic excitation flux Φ_1. According to the law of electromagnetic induction, this flux induces two EMFs E_2 and $-E'_2$ in two sections of the winding W_2. Under the influence of gravity, the anchor 2 moves down in the middle of the magnetic conductor 1 and causes a change in the electromagnetic flux Φ_1 and, respectively, E_2 and $-E'_2$. At the point of electromagnetic symmetry TG we will also receive $E_2 = \left|-E'_2\right|$ and the output signal $U_2 = 0$. When the anchor 2 is moved relative to the point of symmetry down (Fig. 3) or up (Fig. 3, circled with dashed lines) $E_2 \neq \left|-E'_2\right|$, the output signal of the gravimeter will be proportional $U_2 \equiv \left|E_2 - E'_2\right| \equiv mg_z$. In the new two-channel TG, a switch device (SD) 6 was additionally introduced, which is powered by a control voltage source 7, which, at regular intervals of 1 s, switches the supply of the vertical movement of the armature 2 down (Fig. 3) and up (Fig. 3, circled by a dotted line) through motor 5.

When a downward motion pulse is supplied from switch device 6 to armature 2, the output signal f_1 of the sensitive element is fed to the output signal calculation device 8. After 1 s., an upward movement pulse is applied to armature 2 and the output signal calculation device 8 receives a signal f_2. In the device for calculating the output signal 8, the final output signal is formed: $f = f_1 + f_2 = g_Z + \ddot{h} + \Delta i + \Delta w + g_Z - \ddot{h} - \Delta i - \Delta w = 2g_Z$, where $f_1 = g_Z + \ddot{h} + \Delta i + \Delta w$ – output signal when armature 2 moves down; $f_2 = g_Z - \ddot{h} - \Delta i - \Delta w$ – output signal when armature 2 moves up; $\ddot{h}$ – vertical acceleration of the aircraft; Δi – residual instrumental errors; Δw – residual errors from the influence of projections of horizontal cross accelerations on the sensitivity axis of the invention.

That is, in the device 8 for calculating the output signal TG, an output signal equal to the doubled value is formed $2g_Z$. Unlike the transformer converter, the output signal of TG does not have measurement errors caused by the influence of vertical acceleration $\ddot{h}$, residual instrumental errors Δi and residual errors from the influence of horizontal cross accelerations Δw. Thus, it is shown that two-channel TG has a higher accuracy compared to known gravimeters.

4. Development of software for simulation of two-channel TG operation under the action of external perturbing accelerations

If we divide the two-channel TG equation of motion by m, we get:

$$\ddot{x} + 2 \cdot \xi\omega_0\dot{x} + \omega_0^2 x = -2g_z, \tag{7}$$

where ξ – damping factor; ω_0 – natural frequency of a two-channel TG.

Considering that in a real two-channel TG design there will be residual instrumental errors due to temperature effects, changes in medium pressure or other factors, as well as residual errors from the influence of vertical acceleration, which can lead to a non-linearity of the equation of motion of our two-channel TG , we rewrite equation (7) in the form [1, 9]:

$$m\ddot{x} + \dot{x}\left[2n - L\sin(\omega t + \varepsilon)\right] + \omega_0^2 x = N\sin\omega t, \tag{8}$$

where $L = mw_a$, $N = mw_b$ – vibration parameters; w_a, w_b – vibration acceleration amplitudes.

We consider in (8) that $M(t) = 2n - L\sin(\omega t + \varepsilon)$, and $D(t) = \omega_0^2$, then:

$$\ddot{x} + \dot{x}M(t) + D(t)x = 0, \tag{9}$$

where $M(t)$ *and* $D(t)$ – T-periodic functions.

Equation (9) without changing the characteristic indicators can be reduced to a similar one, where $M(t) = const$.

Let be

$$\int_0^t M(t_1)dt_1 = \Psi t + M_1(t), \quad (10)$$

where $\Psi = 2n$; $M(t_1) = \int_0^t (M(t_1) - \Psi)dt = \frac{L}{\omega}\cos(\omega t + \varepsilon)$.

After all mathematical transformations (10), the two-channel TG motion equation can be written as:

$$\ddot{x}' + 2\xi\omega_0\dot{x}' + (\omega_0^2 + v_1 w_b \sin\omega t)x' = 0{,}005\, w_a \sin\omega t, \quad (11)$$

where $v_1 = \frac{v_0}{w_b}$.

Thus, an equation (11) of the Mathieu-Hill type was obtained, taking into account residual errors from the influence of instrumental errors and $\ddot{h}$, which is convenient for computer simulation [1, 9, 10].

The software for modeling the operation of the two-channel TG under the action of external disturbances was developed taking into account (11) in the C# software environment. C# is an object-oriented programming language developed by Anders Galesberg, Scot Wiltamuth and Peter Golde under the auspices of Microsoft Research (at Microsoft).

The software product consists of one working window (Fig. 6), in which the parameters for modeling are set and its results are displayed in the form of Table 1 and graphs (Fig. 4-7).

In Table 1 we will give all the parameters that appear in the calculations and program interfaces.

Table 1

List of used parameters

№	Conventions	Name
1	2	3
1	ξ	Damping factor two-channel TG
2	w	Oscillation frequency
3	w_0	Natural frequency of two-channel TG
4	w_a	The amplitude of the perturbing action along the Oz axis
5	w_b	The amplitude of the perturbing action along the Oy axis
6	t_0	Start time
7	t_{max}	Limit of integration (end time)
8	dt	Integration step
9	m	Mass of the sensing element of the two-channel TG

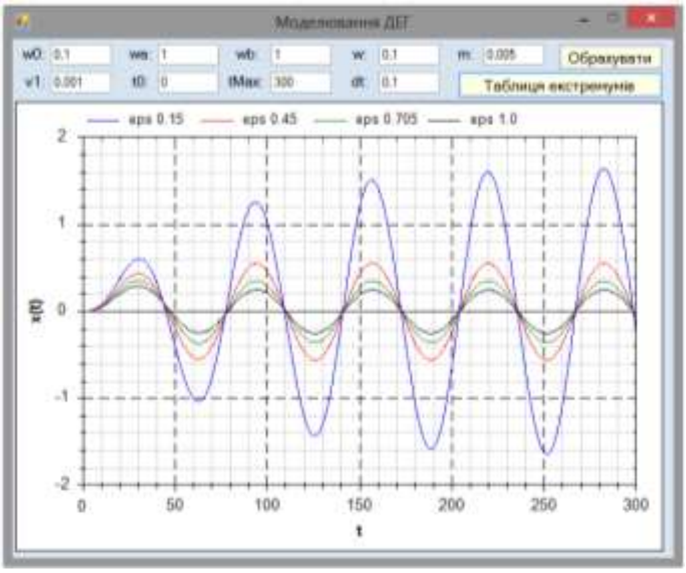

Figure 4. Interface of the computer program for simulating the operation of two-channel TG under the action of external perturbing accelerations

After entering the data in the appropriate fields of the program, for the calculation (or recalculation), you must click on the “Calculate” button — the graphs will change. To get the numerical values of extremes, you need to click on the button “Table of extremes”. The program window will expand (Fig. 5.) and the required table will appear on the right side, as well as a schematic representation of the two-channel TG.

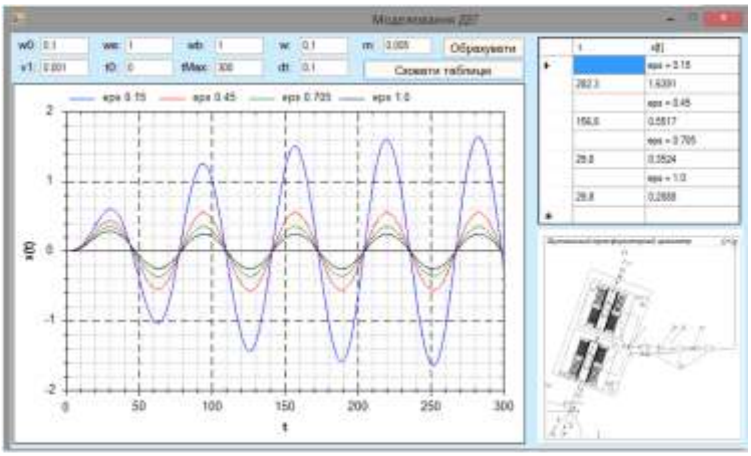

Figure 5. Extended interface of the computer program for modeling the operation of two-channel TG under the action of external perturbing accelerations

5. Results and discussion of computer simulation studies of the influence of unfavorable resonant modes

Thus, the equation of motion that we will model

$$\ddot{x} + 2\xi\omega_0\dot{x} + (\omega_0^2 + v_1 w_b \sin\omega t)x = 0{,}005\, w_a \sin\omega t,\;\; v_1 = \frac{v_0}{w_b}.$$

The parameters of the studied most unfavorable resonant modes are presented in the form of Table 2

Table 2

Parameters of the studied resonance processes

№	ω, c^{-1}	w_a	w_b	ξ			
		м/с^2		0,15	0,45	0,75	1
1		1	1	Resonance	0,110000	0,0661010	0,0496894
2		3	3		0,329914	0,1981360	0,1487170
3	ω_0 =0,1	3	10		0,329782	0,1979630	0,1485420
					1,099710	0,6604540	0,4957240
4		10	3				
5		3	15		0,329687	0,1978360	0,1484160
					1,349570	0,9906820	0,7435860
6		15	3				
7		1	1	0,130020	0,110905	0,0941927	0,0793500
8		3	3	0,389417	0,332314	0,2819150	0,2373970
9	ω_0 /2 =0,05	3	10	0,387163	0,339915	0,2796080	0,2352390
10		10	3	1,298060	1,140430	0,9397170	0,7913230
11		3	15	0,386474	0,338340	0,2779130	0,2338590
12		15	3	1,947090	1,710650	1,4095000	1,1869800
13		1	1	0,110504	0,109731	0,1004580	0,0932015
14	ω_0 /3 =0,03	3	3	0,331016	0,328430	0,3005490	0,2783220
15		3	10	0,329287	0,325772	0,2976650	0,2743310
16		10	3	1,103390	1,094770	1,0018300	0,9277410
17		3	15	0,328061	0,323891	0,2956390	0,2725110
18		15	3	1,65508	1,642150	1,5027400	1,3916100

19		1	1	No resonance Beats	0,0273533	0,0235304	0,0200020
					Continuation of Table 2		
20		3	3		0,0822427	0,0707352	0,0601209
21		3	10		0,0828793	0,0712361	0,0605205
22	$2\omega_0 = 0,2$	10	3		0,2741720	0,2357840	0,2004030
23		3	15		0,0833300	0,0715904	0,6080320
24		15	3		0,4112140	0,3536760	0,3006050
25		1	1	No resonance	0,0120460	0,0105930	0,0097958
26		3	3		0,0362657	0,0316432	0,0294926
27		3	10		0,0367120	0,0320451	0,0298588
28	$3\omega_0 = 0,3$	10	3		0,1208850	0,1054780	0,0983086
29		3	15		0,0370285	0,0323305	0,0301188
30		15	3		0,1813280	0,1582160	0,1474630

Let us represent the obtained graphs of the results of simulation of resonant modes in the form of Fig. 6-7.

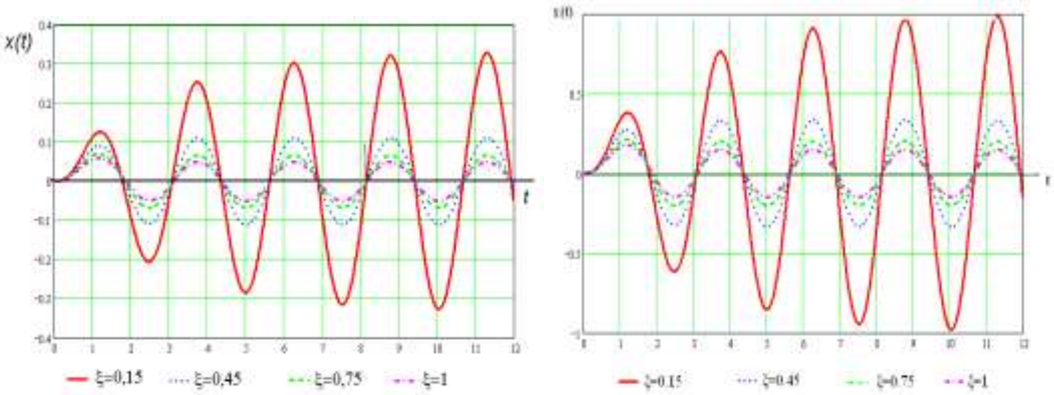

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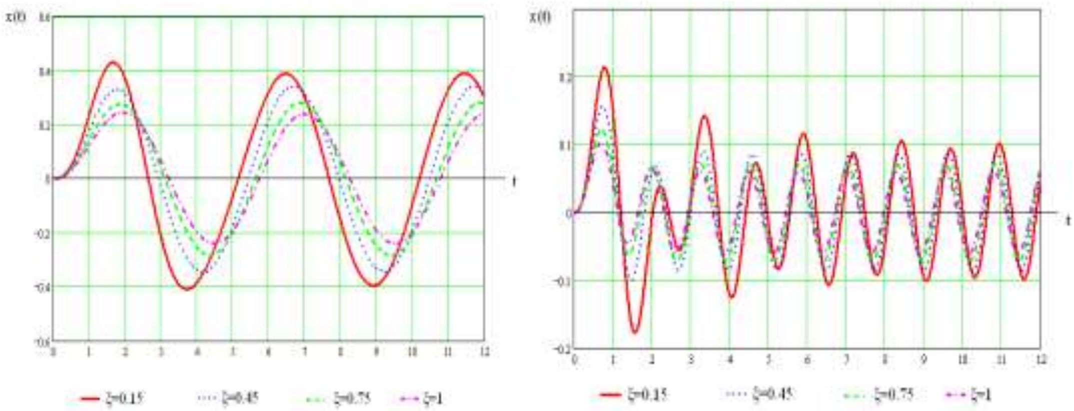
Figure 6. Plot of two-channel TG output signal for different values of the damping factor ζ at $w_a = w_b = 1\, m/s^2$ and $\omega = \omega_0 = 0,1\, s^{-1}$ (a) and ζ at $w_a = w_b = 3\, m/s^2$ and $\omega = \omega_0 = 0,1\, s^{-1}$ (b)



a b

Figure 7. Two-channel TG output plot for different damping ratios ζ at $w_a = w_b = 3\, m/s^2$ and $\omega = \omega_0 / 5 = 0,05\, s^{-1}$ (a) and ζ at $w_a = w_b = 3\, m/s^2$ and $\omega = 2\omega_0 = 0,2\, s^{-1}$.

Analyzing the obtained graphs of two-channel TG operation simulation in the most dangerous resonant modes, presented on Figures 6-7, we can draw the following conclusions:

1) The most dangerous, from the point of view of the possibility of resonance, is only the case of equality of the frequency of the perturbing action ω to the frequency of natural oscillations of the device ω_0, since resonance is possible with low damping $\zeta=0{,}15$. For other frequency ratios ω and ω_0 ($2\omega = \omega_0$, $3\omega = \omega_0$), resonance does not occur even with low damping and different ratios of the amplitudes of disturbing accelerations ($w_a = 1, 3, 10, 15$ and $w_b = 1, 3, 10, 15\ m/s^2$).

With a frequency ratio $\omega = 2\omega_0$, $\omega = 3\omega_0$ and low damping, two-channel TG performs complex oscillations (beats) – the result of the addition of natural oscillations with a frequency of ω_0 and forced oscillations with a frequency of ω. With an increase in the relative damping coefficient ξ at $\omega = \omega_0$, the resonance is already eliminated at $\xi=0{,}45$, and at $\omega = 2\omega_0$, $\omega = 3\omega_0$, the beats turn into steady oscillations, which are carried out with a perturbation frequency ω.

Recommended values of relative damping coefficient $\xi = 0{,}45...0{,}75$ for $\omega = \omega_0$, $\omega = 2\omega_0$, $\omega = 3\omega_0$ and $\xi = 0{,}15...0{,}30$ for $2\omega = \omega_0$, $3\omega = \omega_0$.

2) The conclusion was confirmed that horizontal cross accelerations do not affect the operation of the TG, the amplitudes of the two-channel TG oscillations are directly proportional to the perturbing acceleration along the sensitivity axis.

3) Digital simulation of the influence of disturbing acceleration parameters on the two-channel TG AGS, as well as the instrument's own parameters, confirms the main advantage of two-channel TG over known gravimeters – its higher accuracy (rms error is 0.01 mGal).

Conclusions: formulation of conclusions based on the results obtained; comparison of the obtained results with existing results on the topic; evaluation of scientific novelty and practical value of the obtained results.

Formulation of conclusions based on the results obtained:

- a study of the stability of the new two-channel TG, in accordance with the Nyquist and Hurwitz criteria, showed that DTG is stable;
- as a result of the simulation of the most dangerous resonant modes, graphs of the change in the output signal x(t) of a two-channel transformer gravimeter for different values of the perturbation frequency ω and different values of the amplitudes of disturbing vibrational accelerations wa, wb and different values of the damping coefficient in the most dangerous resonant modes were obtained. It has been established that only the case of the main resonance $\omega = \omega_0$ is the most dangerous. Resonance may occur with a small damping factor. It is shown that as the damping coefficient increases to 0.705, the resonance disappears. For other frequency ratios, resonance does not occur even with a small damping factor;
- digital simulation of the influence of vibrational acceleration parameters on the DTG, as well as its own parameters, confirms the main advantage of the DTG over the known gravimeters — its higher accuracy.

Comparison of the obtained results with existing results on this topic:

the results obtained are not contained in previously published materials.

Evaluation of the scientific novelty of the results obtained:

in this article, the following new results were obtained: for the first time, modeling was carried out and the corresponding graphs of the most dangerous resonant modes of a new two-channel transformer gravimeter were obtained. It is shown that resonance is possible only in the case when the frequency of perturbing vibrational accelerations is equal to the frequency of natural vibrations of the device. It is shown that the resonance is eliminated by increasing the damping coefficient to 0.705. In other cases, resonance does not occur.

Assessment of the practical value of the results obtained:

the practical value of the results obtained in this article lies in the fact that the expediency of the practical use of a new two-channel transformer gravimeter is substantiated, since it has greater accuracy compared to known gravimeters, is stable, has a simple design and a powerful doubled output signal for its operation, does not affect horizontal cross accelerations with any ratio of their frequency and the natural frequency of a two-channel transformer gravimeter.

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Жаңа екі каналды трансформер гравиметрінің жұмысындағы бұзылған діріл үдеуі параметрлерінің әсерін модельдеу

Мақалада автоматтандырылған авиациялық гравиметриялық жүйенің жаңа екі арналы трансформаторлық гравиметрі қарастырылған, оның дәлдігі бүгінгі күні белгілі гравиметрлерден жоғары. Оның дизайны сипатталған. Жаңа екі арналы трансформаторлық гравиметрдің жұмысына бұзылатын діріл үдеуі параметрлерінің әсері модельденді. Екі арналы трансформаторлық гравиметрдің жұмысына аса қолайсыз резонанстық жағдайлар үшін жиіліктер мен қоздырғыш үдеулердің амплитудаларының әсері ЭЕМ көмегімен зерттелді. Өйткені бүгінгі күні екі арналы трансформаторлық гравиметрді авиациялық гравиметриялық жүйенің гравиметрі ретінде қолдану мүмкіндігі мен арнайы мақсатта зерттеуге арналған ғылыми, теориялық және практикалық жұмыстар жоқ. Трансформатордың гравиметрі магнит тізбегінен, жылжымалы арматурадан, бастапқы қоздыру орамынан және екі бірдей секциясы бар қайталама шығыс орамынан тұратын сезімтал элементті қамтиды. Екінші реттік орамның екі секциясы бір-біріне қарама-қарсы жалғанған, ал қозғалмалы якорь қозғалтқышқа қосылады, ол белгілі бір мерзімде якорьді төмен түсіреді және магниттік контур бойымен жоғары көтеріледі, ал қозғалтқышты басқару кернеуінің көзіне қосылған коммутациялық құрылғы басқарады, ал екінші реттік шығыс орамасынан шығатын сигнал шығыс сигналының калькуляторының кірісіне беріледі, онда шығыс сигналы пайда болады, ол гравитациялық үдеудің екі еселенген мәніне пропорционалды. Трансформаторлық гравиметр ұшу аппаратының бортынан гравитациялық үдеу векторының тік құрамдас өлшеу құралдарына жатады және оны геодезия, геофизика саласында, атап айтқанда, Жер шарының жетуі қиын аудандарында тіректік гравиметриялық желіні қалыптастыру кезінде, сондай-ақ ұшақтар мен зымыран жасауда қолдануға болады. Трансформаторлық гравиметр ұшу аппаратында орналасқан авиациялық гравиметриялық жүйенің құрамына кіреді.

Кілт сөздер: екі арналы трансформаторлық гравиметр, қоздырушы әрекет, резонанстық режимдер, бәсеңдету, гравитациялық үдеу.

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Моделирование влияния параметров возмущающих вибрационных ускорений на работу нового двухканального трансформаторного гравиметра

Рассмотрен новый двухканальный трансформаторный гравиметр автоматизированной авиационной гравиметрической системы, точность которого выше известных сегодня гравиметров. Описана его конструкция. Проведено моделирование влияния параметров возмущающих вибрационных ускорений на работу нового двухканального трансформаторного гравиметра. Исследовано с помощью ЭВМ влияние частот и амплитуд возмущающих ускорений для наиболее неблагоприятных резонансных случаев на работу двухканального трансформаторного гравиметра. Ведь сегодня отсутствуют научно-теоретические и практические работы, посвященные исследованиям возможности и целесообразности использования в качестве гравиметра АГС двухканального трансформаторного гравиметра. Трансформаторный гравиметр содержит чувствительный элемент, состоящий из магнитопровода, подвижного якоря, первичной обмотки возбуждения и вторичной выходной обмотки, имеющей две одинаковые секции. Две секции вторичной обмотки соединены последовательно-встречно, а подвижный якорь соединен с двигателем, который с определенным периодом опускает якорь вниз и поднимает вверх по магнитопроводу, причем двигателем управляет устройство переключения, подключенное к источнику напряжения управления, а выходной сигнал со вторичной выходной обмотки подается на вход устройства вычисления выходного сигнала, где генерируется выходной сигнал, пропорциональный удвоенному значению гравитационного ускорения. Трансформаторный гравиметр относится к средствам измерения вертикальной составляющей вектора гравитационного ускорения с борта летательного аппарата и может использоваться в области геодезии, геофизики, в частности, при формировании опорных гравиметрических сеток труднодоступных районов Земного шара, а также в авиа- и ракетостроении. Трансформаторный гравиметр входит в состав авиационной гравиметрической системы, размещённой на летательном аппарате.

Ключевые слова: двухканальный трансформаторный гравиметр, возмущающее воздействие, резонансные режимы, демпфирование, гравитационное ускорение.

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