Vibration Isolation through Magnetic Suspension, Application to Ballistic Gravimeter

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ABSTRACT

The vibration isolation properties of the offered equipments with the moved ferromagnetic core and with double magnetic suspension are considered. The improvement of these properties in comparison with ones of the known magnetic suspension equipments is shown. The magnetic suspension for isolation from vibration in the ballistic gravimeter is presented. The constraction, schemes and parameters of this equipment are presented. The results of the test show that root mean square deviation of the mesurement of the acceleration of the gravity is decreased 2.5 - 7 times with engaged magnetic suspension vibration damper than without one.

INTRODUCTION

It is known, that the magnetic suspension eqipments not only eliminate the mechanical ties, but also isolate the suspended objects from vibration. It is possible to improve the vibration isolation properties of the magnetic suspension equipments with the using the moved ferromagnetic core and with the using double magnetic suspension. The former has the electromagnet with ferromagnetic core fixed on the vibrationed foundation by the using of a mechanical spring and a damper. The latter has two electromagnets. One is fixed on the vibrationed foundation. The second electromagnet is fixed on the object protected from vibration and suspends an additional body, so that this additional suspension absorbs the vibrational energy of the protected body.

THE TRANSFER FUNCTIONS OF THE MAGNETIC SUSPENSION AND BALANCE EQUIPMENTS

Let us consider the magnetic suspension and balance system (MSBS) with one electromagnet on a base, wich make oscillatory movements $y + y(t)$ in the fixed relative to earth system coordinates (figure 1).The linearized equations describing this system into a complex form are:

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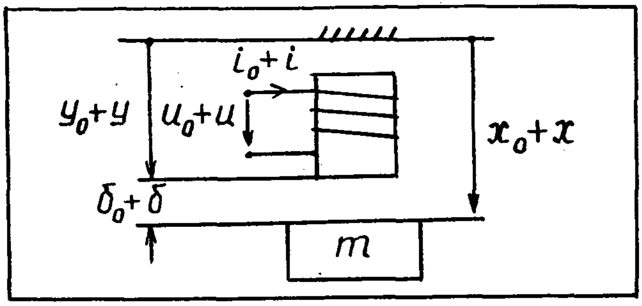


Figure 1.

$$U(j\omega)= H_{11}I(j\omega)+ H_{12}V(j\omega), \quad F(j\omega)=H_{21}I(j\omega)+ H_{22}V(j\omega),$$
$$F(j\omega)=-j\omega m V_m(j\omega), \; U(j\omega)=K_{fb}(j\omega)(V_m(j\omega)-V_b(j\omega))=K_{fb}(j\omega)V(j\omega), \tag{1}$$

where
$$H_{11} = R + j\omega\left(\frac{\partial\Psi}{\partial i}\right)_{i_0;\delta_0}; \; H_{12} = \left(\frac{\partial\Psi}{\partial\delta}\right)_{i_0;\delta_0}; \; H_{21} = \left(\frac{\partial F}{\partial i}\right)_{i_0;\delta_0}; \; H_{22} = \frac{1}{j\omega}\left(\frac{\partial F}{\partial i}\right)_{i_0;\delta_0};$$

R, Ψ - resistance and flux linkages, F - electromagnet force, K_{fb} - coefficient of feedback.

$V_b(j\omega)=j\omega Y(j\omega)$, $V_m(j\omega)=j\omega X(j\omega)$, $V(j\omega)=j\omega\delta(j\omega)$.

From (1):

$$W(j\omega) = \frac{X(j\omega)}{Y(j\omega)} = \frac{H_{21}K_{fb} + H_{11}H_{22} - H_{12}H_{21}}{H_{21}K_{fb} + H_{11}H_{22} - H_{12}H_{21} + j\omega m H_{11}}. \tag{2}$$

It is easy to show, the condition for lack of oscillatory movements of object m $W(j\omega)= 0$ can't be realized in area of stability. The graphs of functional dependences $W(f)$ for case, when it is possibly to take

$$F = \frac{1}{2} B\left(\frac{i_0+i}{\delta_0+\delta}\right)^2 = F_0 + \left(\frac{\partial F}{\partial i}\right)_{i_0;\delta_0} \cdot i + \left(\frac{\partial F}{\partial \delta}\right)_{i_0;\delta_0} \cdot \delta, \tag{3}$$

$$K_{fb}(j\omega) = \frac{\alpha\delta(j\omega) + \beta V(j\omega)}{V(j\omega)} = \frac{\alpha}{j\omega} + \beta, \tag{4}$$

and parametrs of the equipment:

$$F = \frac{B}{2}\left(\frac{i_0}{\delta_0}\right)^2 = 5 \text{ N}, \; i_0 = 1 \text{ A}, \; \delta_0 = 5 \cdot 10^{-3} \text{ m}, \; \left(\frac{\partial\Psi}{\partial i}\right)_{i_0;\delta_0} = 50 \cdot 10^{-3} \text{ H},$$

$$R= 10\,\Omega, \; \left(\frac{\partial F}{\partial i}\right)_{i_0;\delta_0} = \left(\frac{\partial\Psi}{\partial\delta}\right)_{i_0;\delta_0} = \frac{B\, i_0}{\delta_0^2} = 10 \text{ N/A}, \; \left(\frac{\partial F}{\partial\delta}\right)_{i_0;\delta_0} = -2 \cdot 10^3 \text{ N/m},$$

$\beta = 40$ V.s/m., are shown in figure 2.

The vibration isolation may be improve much more, if additional signal determined by acceleration of object m is introduced in the controlling tension:

$$U(j\omega) = K_{fb}(j\omega)V(j\omega) + j\omega\gamma V_m(j\omega), \tag{5}$$

where γ - coefficient.

Using (5) we get the transfer function

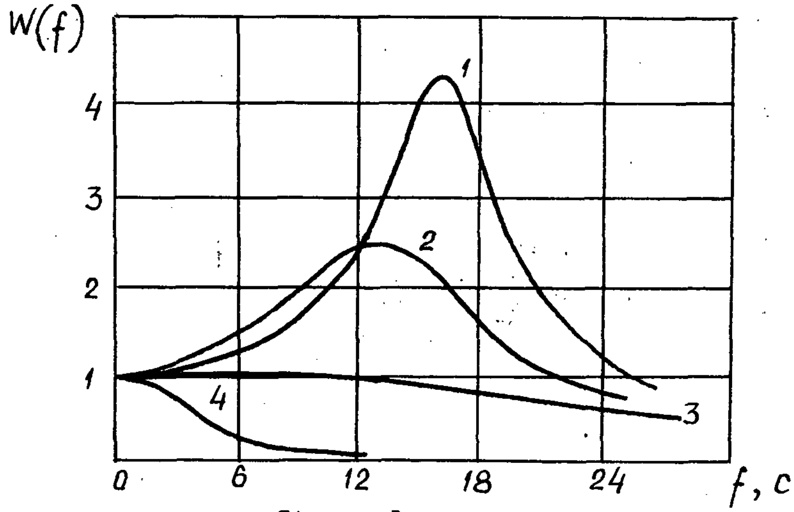


Figure 2.

1- α = 7.10 V/m, β = 40 V.s/m, γ =0, 2- α= 5.10 V/m, β = 40 V.s/m, γ =0,
3- α = 2.10 V/m, β = 40 V.s/m, γ =0, 4- α=10 V/m, β=40 V.s/m, γ=20 V.s /m

$$W(j\omega) = \frac{H_{21} K_{f\beta} + H_{11} H_{22} - H_{12} H_{21}}{H_{21} K_{f\beta} + H_{11} H_{22} - H_{12} H_{21} + j\omega m H_{11} + j\omega\gamma H_{21}} \qquad (6)$$

The graph of functional dependence W(f) according (6) is shown in figure 2 .

It is demanded to place the accelerometer on the suspended object for introducing the acceleration in the controlling tension. It isn't always acceptability. The effectiveness of the vibration isolation may be increase too by the use of the equipment which is shown on figure 3. This equipment has the electromagnet with ferromagnetic core, which is fixed on vibrationed foundation by the using of mechanical spring with hard coefficient k and damping coefficient k .

Linearized equations describing the equipment in figure 3 are:

$$U(j\omega) = H_{11} I(j\omega) + H_{12} V(j\omega), \quad F(j\omega) = H_{21} I(j\omega) + H_{22} V(j\omega),$$

$$U(j\omega) = K_{f\beta} V(j\omega), \quad \delta = X_m - X_c, \quad j\omega\, m(V_c(j\omega) + V(j\omega)) = -F(j\omega), \qquad (7)$$

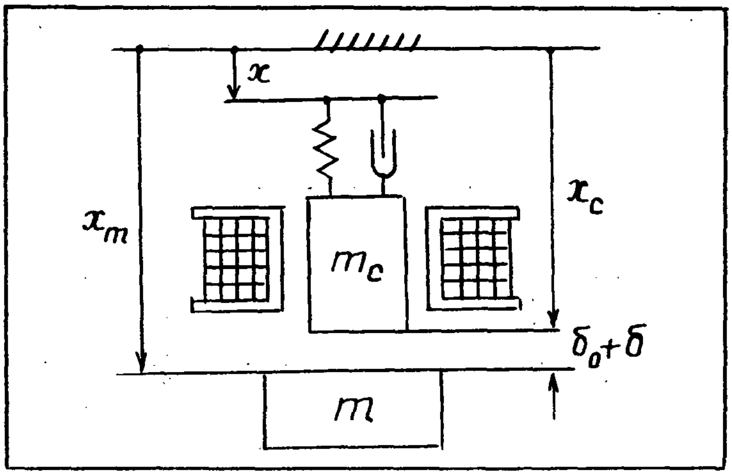
$$j\omega\, m_c V_c(j\omega) = F(j\omega) - k(X_c(j\omega) - X\ (j\omega)) - k_d(V_c(j\omega) - V\ (j\omega)).$$

where m , m_c - masses of the suspensed object and the core,

$$V_c(j\omega) = j\omega X_c(j\omega), \quad V(j\omega) = j\omega X(j\omega).$$

When the coefficient of the feedback is determined according (4) from (7) we get :

$$W(j\omega) = \frac{X_m(j\omega)}{X(j\omega)} = \frac{(b_0 - \omega^2 b_2) + j\omega b_1}{(a_0 - \omega^2 a_2 + \omega^4 a_4) + j(\omega a_1 - \omega^3 a_3 + \omega^5 a_5)} \qquad (8)$$



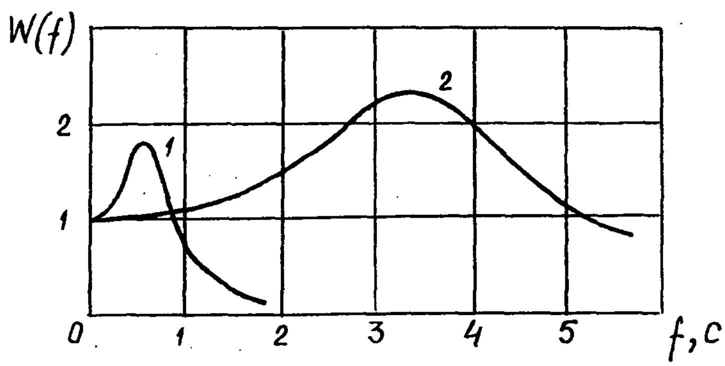


Figure 4.

1-MSBS with the moved core, $\alpha = 1,6.10^3$ V/m, $\beta = 10$ V.s/m, $m_c = 0,43$ kg, m=7 kg;
2-MSBS with the fixed core, $\alpha = 1,6.10^3$ V/m, $\beta = 10$ V.s/m, m =7 kg

where

$$a_0 = b_0 = kM\ ,\quad a_1 = b_1 = kN + k_d M\ ,\quad b_2 = k_d N\ ,$$

$$a_2 = (m + m_c)M + mkR + k_d N,\qquad a_3 = (m + m_c)N + m\left(k\left(\frac{\partial\Psi}{\partial i}\right)_{i_0,\delta_0} + k_d R\right),$$

$$a_4 = m\left(m_c R + k_d\left(\frac{\partial\Psi}{\partial i}\right)_{i_0,\delta_0}\right)\ ,\qquad a_5 = m m_c\left(\frac{\partial\Psi}{\partial i}\right)_{i_0,\delta_0},$$

$$M = \left(\frac{\partial F}{\partial i}\right)_{i_0,\delta_0} + \left(\frac{\partial F}{\partial \delta}\right)_{i_0,\delta_0} R\ ,\qquad N = \left(\frac{\partial F}{\partial i}\right)^2_{i_0,\delta_0} + \beta\left(\frac{\partial F}{\partial i}\right)_{i_0,\delta_0} + \left(\frac{\partial F}{\partial \delta}\right)_{i_0,\delta_0}\left(\frac{\partial\Psi}{\partial i}\right)_{i_0,\delta_0}$$

Figure 4 shows the functional dependence W(f) according (8), when for electromagnet force it is possibly to take (3) and parametrs of the equipment: $m_c = 0,43$ kg, m = 7 kg, $\delta_0 = 5.10^{-3}$ m, R = 2,5Ω, $(\partial\Psi/\partial i)_{i_0,\delta_0} = 80.10^{-3}$ H, $(\partial F/\partial i)_{i_0,\delta_0} = 47$ N/A, $(\partial F/\partial \delta)_{i_0,\delta_0} = 28.10^3$ N/m, $k = 10^2$ N/m, $k_d = 20$ N.s/m.

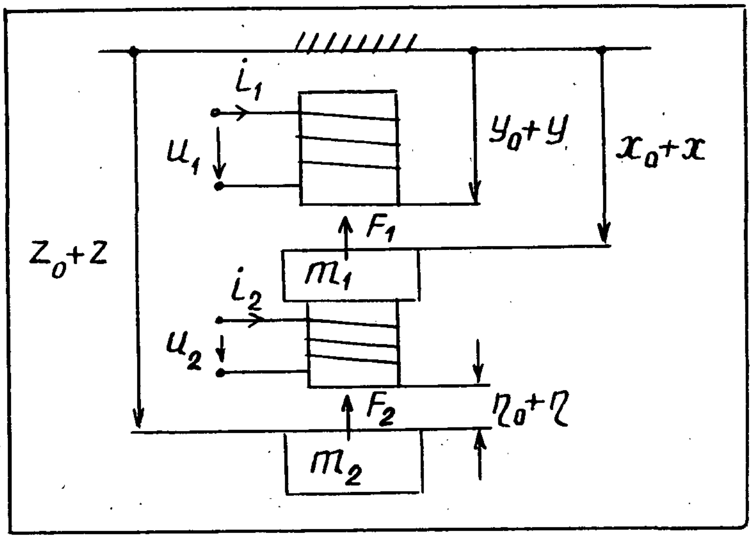


Figure 5.

The comparison of the transfer functions by the magnetic suspension and balance equipments with fixed and travelling cores (curves 1 and 2 on figure 4) shows, that the bound frequency of the effective damping vibration area reduces thanks to using travelling core.

The effectiveness of the vibration isolation may be increased without accelerometer by the using of the equipment with double magnetic suspension wich is shown in figure 5. This equipment has two electromagnets. One is fixed on the vibrationed foundation. Some object is protected from the vibration of this foundation.The second electromagnet is fixed on this object and suspends an additional body, so that this additional suspension absorbs the vibrational energy from the protected body. The linearized equations describing this system into a complex form are

$$
\begin{aligned}
&U_1(j\omega) = H_{11}I_1(j\omega) + H_{12}V_\delta(j\omega), \quad F_1(j\omega)=H_{21}I_1(j\omega)+H_{22}V_\delta(j\omega),\\
&U_2(j\omega) = h_{11}I_2(j\omega) + h_{12}V_\eta(j\omega), \quad F_2(j\omega)=h_{21}I_2(j\omega)+h_{22}V_\eta(j\omega),\\
&F_1(j\omega)-F_2(j\omega)= - j\omega m_1V_x(j\omega), \quad F_2(j\omega) = - j\omega m_2V_z(j\omega),\\
&U_1(j\omega) = K_{11}V_\delta(j\omega)+ K_{12}V_\eta(j\omega), \quad U_2(j\omega) = K_{21}V_\delta(j\omega)+ K_{22}V_\eta(j\omega).
\end{aligned}
\qquad (9)
$$

where: $V_\delta(j\omega)= j\omega\delta(j\omega)$, $V_\eta(j\omega)=j\omega\eta(j\omega)$, $V_x(j\omega)= j\omega X(j\omega)$,

$V_z(j\omega)= j\omega Z(j\omega)$, $K_{\ell\rho}$ - the complex transfer functions of the regulators.

If $u_1=\alpha_{11}\delta + \beta_{11}\dot{\delta} + \alpha_{12}\eta+ \beta_{12}\dot{\eta}$, $u_2=\alpha_{22}\eta+ \beta_{22}\dot{\eta}$,

from (9) we get

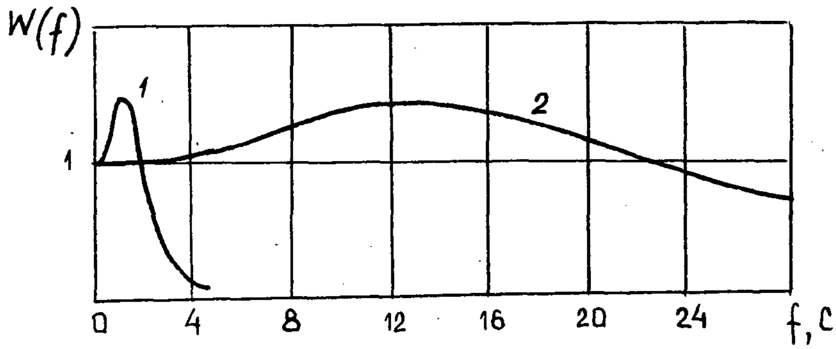


Figure 6.

1- $\alpha_{11} = 2,5.10^3$ V/m, $\alpha_{22} = 1,25.10^3$ V/m, $\beta_{11} = 300$ V.s/m, $\beta_{22} = 50$ V.s/m, $\alpha_{12} = 0$, $\beta_{12} = -25.10^3$ V.s/m,

2 - $\alpha_{11} = 5.10^3$ V/m, $\alpha_{22} = 1,25.10^3$ V/m, $\beta_{11} = 60$ V.s/m, $\beta_{22} = 20$ V.s/m, $\alpha_{12} = 0$, $\beta_{12} = 0$.

$$W(j\omega) = \frac{x(j\omega)}{y(j\omega)} = \frac{(b_0 - \omega^2 b_2 + \omega^4 b_4) + j(\omega b_1 - \omega^3 b_3)}{(a_0 - \omega^2 a_2 + \omega^4 a_4 - \omega^6 a_6) + j(\omega a_1 - \omega^3 a_3 + \omega^5 a_5)} \qquad (10)$$

where

$$a_0 = b_0 = QS, \quad a_1 = b_1 = QH + SG, \quad b_2 = m_2 R_2 Q + GH, \quad b_3 = m_2 \frac{\partial \psi}{\partial i} Q + m_2 R_2 G,$$

$$b_4 = m_2 \frac{\partial \psi_2}{\partial i_2} G, \quad a_2 = (m_1 + m_2) R_1 S + m_2 R_2 \left(Q - \alpha_{12} \frac{\partial F_1}{\partial i_1}\right) + GH,$$

$$a_3 = (m_1 + m_2)\left(R_1 H + \frac{\partial \psi_1}{\partial i_1} S\right) + m_2 \left(Q - \alpha_{12} \frac{\partial F_1}{\partial i_1}\right) \frac{\partial \psi_2}{\partial i_2} + m_2 R_2 \left(G - \beta_{12} \frac{\partial F_1}{\partial i_1}\right),$$

$$a_4 = m_1 m_2 R_1 R_2 + (m_1 + m_2) \frac{\partial \psi_1}{\partial i_1} H + m_2 \frac{\partial \psi_2}{\partial i_2} \left(G - \beta_{12} \frac{\partial F_1}{\partial i_1}\right),$$

$$a_5 = m_1 m_2 \left(R_1 \frac{\partial \psi_2}{\partial i_2} + R_2 \frac{\partial \psi_1}{\partial i_1}\right), \qquad a_6 = m_1 m_2 \frac{\partial \psi_1}{\partial i_1} \cdot \frac{\partial \psi_2}{\partial i_2},$$

$$Q = \alpha_{11} \frac{\partial F_1}{\partial i_1} + R_1 \frac{\partial F_1}{\partial \delta}, \qquad S = \alpha_{22} \frac{\partial F_2}{\partial i_2} + R_2 \frac{\partial F_2}{\partial \eta},$$

$$G = \left(\frac{\partial F_1}{\partial i_1}\right)^2 + \beta_{11}\left(\frac{\partial F_1}{\partial i_1}\right) + \frac{\partial F_1}{\partial \delta} \cdot \frac{\partial \psi_1}{\partial i_1}, \qquad H = \left(\frac{\partial F_2}{\partial i_2}\right)^2 + \left(\frac{\partial F_2}{\partial i_2}\right) + \frac{\partial F_2}{\partial \eta} \cdot \frac{\partial \psi_2}{\partial i_2}.$$

All partial derivatives in the expressions for the coefficient in (10) are taken in the point $i_1 = i_2 = 0$, $\delta = \eta = 0$.

Figure 6 shows the functional dependence W(f) according (10), if for electromagnet forces F_1 and F_2 possible to take (3) and parametrs of the equipment are:

$m_1 = 0,5$ kg, $m_2 = 0,1$ kg, $R_1 = 10\,\Omega$, $R_2 = 5\,\Omega$, $\partial\Psi_1/\partial i_1 = 50\ 10^{-3}$ H, $\partial\Psi_2/\partial i_2 = 10\ 10^{-3}$ H, $\partial F_1/\partial i_1 = 10$ N/A, $\partial F_1/\partial\delta = -2.10^{-3}$ N/m, $\partial F_2/\partial i_2 = 2$ N/A, $\partial F_2/\partial\eta = -0,4\ 10^{3}$ N/m, .

The comparison the graphs 1 and 2 in figure 6 shows the influence on the vibration isolation properties the introducing in the first electromagnet's controlling tension the signals depended from the velocity of the clearences change between protected object and the additional body.

The equipment with double magnetic suspension is similar to mechanical equipment with an absorber of the vibratory energy.

GRAVIMETER

The magnetic suspention was used for isolation from vibration in the ballistic gravimetr. The ballistic gravimeters are using for the measurement of the acceleration of the gravity, one is calculated in accordance with the measured distance passed by body in vacuum and the time spent for this distance. Figure 7 shows the scheme of the ballistic gravimeter using magnetic suspention. The equipment has a catapult thrown up the body - angular reflector 1 - in vacuum. During moving upwards and down this body passes through the same two points, being on different height. The measurement of the distance passed by body is made by the use of the laser interferometer with laser 2 and the photoelectric transformer 3, formed the pulses, wich quantity correspond to the quantity of the half-lengths of the wave, passed by the body between the points being on different height. The time spent for this distance is measuremented by the use of the quartz generator.

The measurement of the distance should make relatively to base of the gravimeter. The vibration of the base creates the error of the measurements. The angular reflector 4 fixed on magnetic suspensed body is used as a base for measurements for decrease this error.

Magnetic suspension is realized with using a solenoid 5. A core 6 from soft magnetic material is suspensed in the magnetic field of the solenoid in the stable position along the vertical axis. This core with the reflector 4 fixed on it is the inert element of the system isolated from vibration. Two contactless electromagnetic supports 7 with resonant circuits are used for centring.

The controll of the solenoid's current is made by using of the singals of the acceleration, of the velocity, of the inert element's travel. The accelerometer fixed on the core of the solenoid is shown on the figure 8. The electromagnetic support with resonant circuits is used to tie of the accelerometer's inert element with base of the accelerometer. There are two electromagnets 1 and 2. The inert element presents a ferrite washer, wich can to move only along the sensible axis on account of the limitation of the tape stretching 7. The stable suspension of the ferrite washer is provided with the instrumentality of the resonant circuit C2, L2. All mechanical part is diped into oil for damping of the oscillations of the inert element.

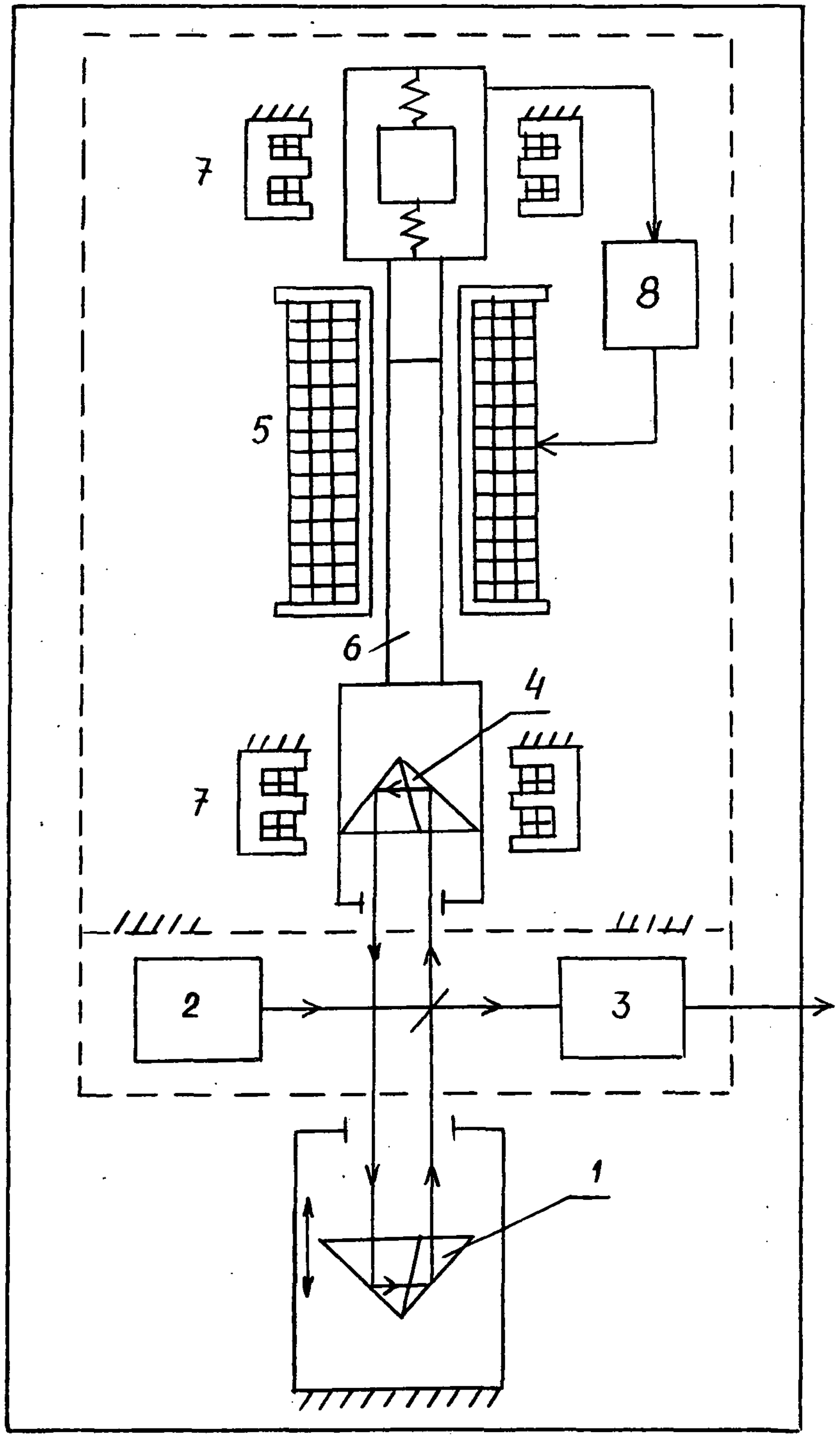


Figure 7.

1 - angular reflector, 2 - laser, 3 -photoelectric transformer, 4 - angular reflector, 5 - solenoid, 6 - core, 7 - electromagnetic supports, 8 - current regulator.

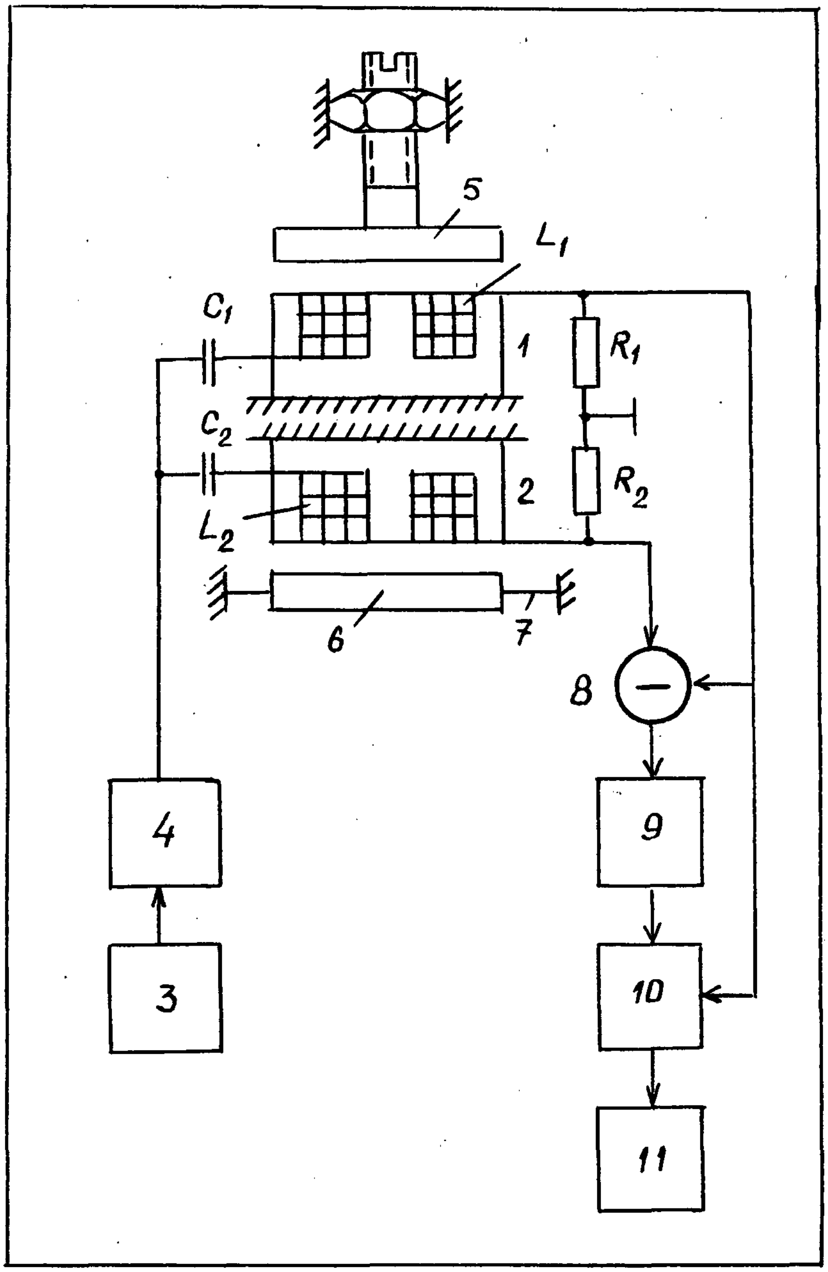


Figure 8.

1,2 - electromagnets, 3 - quartz oscillator, 4 - amplifier, 5 - ferrite wosher, 6 - inert element, 7 - tape stretching, 8 - comparator, 9 - amplifier, 10 - phase detector, 11 - filter.

The electronic part of the interferometer contains the alternating current source for the electromagnets with the quartz generator of 20 kc and the power amplifier.

The resonant circuits are turned in the sunk part of the resonance characteristic of the current, in such a way that signals across the resistances R1 and R2 have equal amplitudes and phases with the absence of the inert acceleration and in the statical position of the inert element. The measurement channel include the compare device 8, the amplifier 9, the phase detector 10, the filter 11.

The test of the ballistic gravimeter was condacted in two series: with engaged the vibration damper and with switching-off the vibration damper. The test was conducted with placing the gravimeter on the gyrostabilized platform and without it for clearing up possibility to damp a vibration made by the gyromotors. The gyrostabilized platform was placed on the bracket fixed on wall wich seismic background was a considerable extent less than the seismic background of floor.

The results of the test are shown in the table

TABLE 1 - THE RESULT OF THE TEST

The Vibration:	The indastrial Vibration		The Vibration by the gyrostabilized platform
Quantity of measurements	49	52	110
Root mean square deviation with switching-off vibration damper, 10 m/s	1,4	2,4	3,06
Root mean square deviation with engaged vibration damper, 10 m/s	0,6	0,7	0,44

CONCLUDING REMARKS

The getting transfer functions of the magnetic suspension and balance equipments determine the possibility of the using ones for the vibration isolation. It is shown possibility the improving the vibration isolation properties of the magnetic suspension equipments with the moved ferromagnetic core and with double magnetic suspension.

The using of the magnetic suspension for isolation from vibration in the ballistic gravimeter decreased of the measurement's mistake of the acceleration of gravity 2,5 - 7 times.