Device of dynamic settings of dynamically tuned gravimeter

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Abstract — The paper presents a dynamic device designed to dynamically tuned gravimeter, which is driving the change speed rings gimbals through the use of electronic means of the controlled engine. Mathematical research of electric drive was completed. The developed device allowed simplifying the process of dynamic configuration of gravimeter.

Index Terms — electric motor, gravimeter, dynamic tuning, gimbals, electric motor, aircraft gravimetric system

1 INTRODUCTION

Gravimeters are used in mineral prospecting, seismology, geodesy, geophysical surveys and research. In [1-3] found that for a given precision double-ring dynamically tuned gravimeter aircraft gravimetric system to ensure its dynamic setting. Equation considering members change with $2\dot{\gamma}$ frequency is cumbersome. The solution of these equations also heavily burdened members with variable coefficients. Members of changing the frequency $2\dot{\gamma}$ can be eliminated by structural means, and it is necessary to develop a dynamic setting device gyroscopic gravimeter [4-6]. To study the characteristics of the Earth's gravitational field in inaccessible parts of the globe, the aircraft gravimetric system (AGS) is necessary [7-9]. Accuracy of the Earth gravity anomalies measurement using gravimetric aviation system is largely dependent on the choice of system's sensing element. Today, the gyroscopic gravimeters are considered to be one of the most effective among the available solutions.

The aim of this paper is to develop a device of dynamic settings of dynamically tuned gravimeter.

Providing dynamic configuration of dynamically customized gravimeter by changing the speed of the rings gimbals is possible if the rotor of an engine is controlled by electronic means.

In order to provide high-speed stability there should be a possibility to measure this frequency. For this purpose, the engine must have speed sensor rotor. Electric valve of direct current, that includes two phase stator windings, permanent magnet rotor and two rotor position sensors (RPS) has these characteristics. Each of the RPS is a winding, which provides a permanent magnet rotor circular electric field whose frequency is equal to the speed of rotation of the rotor, multiplied by the number of pole pairs of the rotor. The rotor rotates due to interactions between the circular stator of the electric field and a field of permanent magnet rotor. The circular stator electric field is formed by two channels power phase windings of value electric motor, located in the engine control unit of gravimeter. This engine is well guided by electronic means, provides high-speed stability due to its automatic control; overheating is small. This raises the possibility to locate speed setting items, i.e. dynamic settings of gravimeter in the engine control unit (ECU).

Description of the device of dynamic configuration. The principle is explained by functional electric circuit of gravimeter, shown in Fig. 1.

The rotor 1, rigidly suspended on stable gimbal 2 with elastic ridges 3, using axis 4 is fixed in the inner ring of ball of support 5 fixed in the hull 6.

The electric rotor 1 is made being based on a direct current brushless motor (BM) which includes two phase windings 7 and two rotor position sensor 8 fixed in the hull 6 and rotor brushless motor 9 mounted on the axis of the inner ring of ball bearing support 5.

ECU 8 connected to the input supply voltage reference digital-to-analog converters 10, 11, performed at the chip 572PA1 and zero-body by 12, 21, performed at the comparator 521SAZ. Out of one of these zero-bodies 12 connected to the input pulse shaper with a duration period of the fluid rotation of the rotor 13, made on the basis of binary counter 533YE5 and logic element 2I-NE 533LA3. Output pulse shaper with a duration period of the fluid rotation of the rotor 13 is connected to one of the inputs trigger mark the difference of the reference period and the fluid rotation of the rotor 14, performed at the D-trigger 533TM2, one of the inputs of discrete impulse generator to the duration of the reference period, with adjustable rotor conversion factor of this period 15, made on the basis of cascade-connected controllers of synchronization 585HL4 and one of the input pulse shaper, which number is directly proportional to the difference of the reference period and the fluid rotation of the rotor 17, made on the basis of logical element or 533LP5.

Output of master oscillator 16, made on the basis of thermal-compensated TCF4GOC16C20.000 generator with frequency 20MHz, connected to the second input pulse shaper guestrooms proportionately to difference between reference

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period and fluid rotation of the rotor 17 and the second input pulse shaper discrete reference period with a duration rotor of this period 15. Output of the last is connected to the second input trigger mark of difference between reference period and fluid rotation of the rotor 14 and third input pulse shaper, whose number is directly proportional to the difference of the reference period and the fluid rotation of the rotor 17.

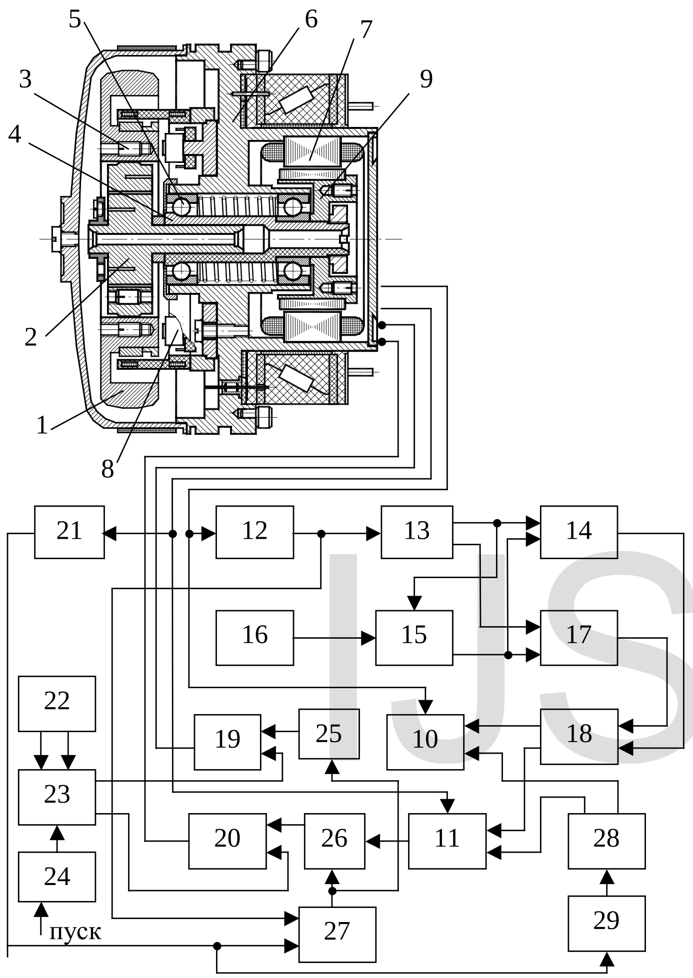

Fig. 1. Functional scheme electrical drive of gravimeter with electronic motor

Outputs trigger mark of difference between reference period and fluid rotation of the rotor 14 and pulse shaper guestrooms which is directly-proportional to the difference between the reference period and the fluid rotation of the rotor 17 connected to the inputs of the counter forward and reverse counting pulses 18, made on the basis of reversible binary counter 533YE7, which exits connected to other inputs of digital-to-analog converters 10, 11, and their outputs are connected to the power amplifiers 19, 20, made on the basis of high-voltage operational amplifiers and transistors 1408UD1 2T818, 2T819. Out of the second of zero-body 21 is connected to the trigger inputs with direction of rotation guides 27 and 29. Trigger output direction of rotation 27 is connected to the input control key 25, 26, which connect the circuit at the inputs of power amplifiers 19, 20 outputs of digital-to-analog converters 10, 11. The output 29 is connected to the input threshold device 28, which is performed at the chip 140UD6. Output threshold device 28 is connected to the senior level digital-to-analog converters 10, 11. Output delay units 24 is connected to the input control key 23, which connects in circuit outputs with two-phase low-frequency generator 22 with inputs of power amplifiers 19, 20. The outputs of power amplifiers 19, 20 are connected to the stator phase windings BM 7.

Powered electric rotor works in the next way. When a command "Start" link of delay 24, on interval of 3-4 s gives a signal which merges electronic key 23 through which the two-phase sinusoidal voltage with low frequency oscillator 22 goes to the power amplifiers 19, 20. Through these amplifiers, voltage is applied to two-phase valve motor phase windings and rotor 9 begins to rotate in a given direction. Trigger of direction of rotation 27 on signals from the zero-body of 12, 21 detects the beginning of the rotation in a given direction and issues a signal on which electronic keys 25, 26 are locking. Through these key two-phase sinusoidal voltage, which is formed as a digital-to-analog converters 10, 11 is fed to the power amplifiers 19, 20, and are in the phase windings BM. The rotor 9 begins to pick up speed. Link of delays 24 turns off electronic key 23 to input amplifiers 19, 20, signals from the low-frequency generator 22 is not served. The signal from the zero-body 21 through guides 29 reaches the threshold device 28. When the rotation speed values close to synchronous (5% - 10% lower) threshold device 28 resets level (10) category of each of the digital-to-analog converters 10, 1. The rotor 9 continues to accelerate smoothly and goes in synchronism. Stability rotor angular velocity begins to work.

While rotating rotor 9 in ECU 8 provides sinusoidal voltage with frequency directly proportional to the frequency of rotor 9. This voltage is fed to the input reference voltage digital-to-analog converters 10, 11 and zero-bodies 12, 21 that make the last in rectangular pulses duration which is directly proportional to the period of rotation of the rotor 9, and therefore the rotor and gimbals 2.

A rectangular pulse produced by zero-body 12, the duration of which is directly proportional to the signal period ECU 8, enters the pulse shaper with a duration period of the fluid rotation of the rotor 13, which produces pulses with a duration period of the fluid rotation of the rotor.

Pulses with a duration period of the rotor come to one of the inputs trigger mark difference of reference period and fluid rotation of the rotor 14, one of the inputs pulse shaper, whose number is directly proportional to the difference of the reference period and the fluid rotation of the rotor 17, one of the inputs of discrete pulse shaper reference the period of rotation of the rotor with adjustable conversion factor of this period 15 to run last, the second input is received master oscillator pulse 16. The pulses with a duration period of the rotor fluid fed to one of the inputs trigger mark the difference of the reference period and the fluid rotation of the rotor 14 the second input of which receives a discrete pulse generator pulse with a duration period of the reference rotor with adjustable conversion factor of this period 15.

Pulses discrete pulse shaper reference period rotor with adjustable conversion factor of this period 15 lead to a second trigger input reference and mark the difference of the fluid rotation period of the rotor 14 and the second input pulse shaper, whose number is directly proportional to the difference of the reference period and the fluid rotation of the rotor 17, the third input is receiving pulses requested at thermally compensated generator 16.

The pulses trigger mark difference reference period and fluid rotation of the rotor 14 and pulse shaper, whose number is directly proportional to the difference of the reference period and the fluid rotation of the rotor 17 receives the inputs of the counter forward and reverse counting pulses counter 18. Counter produces 9-bit control codes coming to digital converters 10 and 11, generating control voltages that, being enhanced by power amplifiers 19 and 20, come in at phase stator winding BM 8, providing rotor 9. This is possible due to the identity phase windings and stator 8 ECU.

Changing the speed of the rotor 9 will continue until the period of the pulse generator pulse with a duration period of the fluid rotation of the rotor 13 will be equal to the period of the pulse shaper discrete pulse with a duration period of the reference rotor with adjustable conversion factor of this period 15. The difference between reference and fluid period of rotor output pulse shaper guestrooms proportionately difference reference periods and fluid rotation of the rotor 17 will be zero and, consequently, the output code counter forward and backward counting pulses 18 will not be changed. Signal at output of digital-to-analog converters 10, 11 will not vary, and the rotor speed is maintained before formed control voltage output amplifiers 19, 20.

If during the dynamic configuration of ECU is necessary to change the value of the turning points in the centrifugal inertia rings gimbals 2, by changing the speed of the rotor 1, the conversion factor adjustable pulse shaper discrete reference period with a duration adjustable conversion factor of this period 15. As a result the length reference period of rotation of the rotor changes. Furthermore, the work of device is going to continue according to previously described method with the established rotor speed conversion factor determined by the modified discrete pulse shaper reference period rotor with adjustable conversion factor of this period 15.

Changing the speed of the rotor causes the change of turning centrifugal moments of inertia rings gimbals 2 and resilient balancing recoverability jumpers gimbals 2. Thus, the condition of ECU dynamic settings is completed.

K ratio recalculation of reference period rotor discrete pulse shaper reference period can be found using the formula [10]

$$K = 2^{4n} - (\lambda - \lambda_F)F\,, \tag{1}$$

where n – number of series-connected controllers of synchronization 585HL4 (in ECU n=4), *F* - specifying the frequency, which is formed by the generator 16, λ - rotor current period ECU, λ_F - pulse duration setting frequency *F*.

When F=107 Hz, $\lambda_F = 0{,}5 \cdot 10^{-7} s$. At nominal rotor speed $f_0 = 200$ Hz, $\lambda_0 = f_0^{-1} = 5 \cdot 10^{-3} s$ - reference period of rotation of the rotor. Substituting (1) nominal values, we obtain nominal conversion factor reference period to be equal *K=15537*.

Formula (1) results that current period of rotation of rotor ECU totals $\lambda = (65536 - K + 0{,}5) \cdot 10^{-7}$ s.

As can be seen from this formula, by changing the *K* ratio, unit λ changes into 10^{-7} s, and rotor speed - the magnitude $200 - (5 \cdot 10^{-3} + 10^{-7})^{-1} = 0{,}004$ *Hz*, i.e. the 0,002%. The maximum value of the current period, according to the same formula will be at *K=0* and equals $\lambda = 0{,}0065536$ *s*. This value corresponds to the minimum rotor speed $f_{\min} = 152{,}6$ *Hz*. The maximum value of the limited frequency *F*. Practically equals to 250 Hz.

Mathematical researches of work of electrical drive.

Equation of work of electrical drive. Supply voltage of each phase of valve electric motor provides phase current and compensates counterpower that occurs in the winding [1]. Therefore, this voltage is,

$$U = IR_w + E \tag{2}$$

where *I* - the current in the phase windings of valve electric motor, R_w- phase winding resistance (inductance, due to its small size, is neglected), *E*- counter electrical power.

$$E = C_E \omega(t), \tag{3}$$

where C_E - the proportionality between the angular speed of the rotor and power counter electrical power, $\omega(t)$- rotor angular velocity, *t* – current time.

The moment that engine develops is

$$M = C_M I\,, \tag{4}$$

where C_M - the proportionality between the mechanical aspect, which operates a rotor and a phase current I stator.

Counting that the angular acceleration of the rotor is

$$\frac{d\omega(t)}{dt} = \frac{M - M_{rr}}{J}, \tag{5}$$

where *J* - total moment of inertia of valve electric motor and gyroscope rotors, M_{rr} - moment of resistance to rotation of the rotor.

From formulas (3-5) we find.

$$\frac{d\omega(t)}{dt} = C_M \frac{U - C_E \omega(t)}{JR_{об}} - \frac{M_{on}}{J} \tag{6}$$

Using Laplace operator p, equation (6) can be rewritten as follows:

$$p\omega(t) + \frac{C_M C_E \omega(t)}{JR_{об}} = \frac{C_M}{JR_{об}} U - \frac{M_{on}}{J}\,. \tag{7}$$

From the last equation we obtain the transfer function of valve electric motor:

$$\omega(t) = \frac{k_d U}{T_d p + 1} - \frac{T_d}{T_d p + 1} \frac{M_{on}}{J}, \tag{8}$$

where $T_d = \dfrac{JR_{об}}{C_M C_E}$ - electromechanical time constant of valve electric motor, $k_d = C_E^{-1}$ - transfer ratio of valve electric motor.

The numerical values of the following options of value electric motor: $C_M = \dfrac{15 gsm}{0{,}155 A}$, $C_M = 96{,}774 \dfrac{gsm}{A}$,

$C_E = \frac{12{,}2V}{1256s^{-1}}$, $C_E = 9{,}71 \cdot 10^{-3} Vs$, $R_{об} = 18{,}7\Omega$, $J = 0{,}25\, gsm*s^2$, $T_d = 4{,}97\, s$, $k_d = 103\ V^{-1}s^{-1}$.

Inductance of winding is L=0,16 *mH*, so it can be neglected.

From the expression (7) the following formula for the angular velocity of the rotor, can be obtained

$$\omega(t) = k_d\left(1 - e^{-\frac{t}{T_d}}\right)\left(U - \frac{T_d}{k_d}\frac{M_{on}}{J}\right) + \omega_0 e^{-\frac{t}{T_d}} \qquad (9)$$

where ω_0 - initial condition.

Equation of work of the electrical drive. Given that ECU output voltage is proportional to integral formed from the difference of periods

$$\Delta T = T_c - T_e$$

where T_c - rotor current period, T_e - reference period of rotation of the rotor, $T_e = 5 \cdot 10^{-3}\ s$, then formula (9) may be as follows

$$\omega(t) = k_d\left(1 - e^{-\frac{t}{T_d}}\right)\left(k_n T_k - \frac{T_d}{k_d}\frac{M_{on}}{J}\right) + \omega_0 e^{-\frac{t}{T_d}}, \qquad (10)$$

where k_n - ECU transfer ratio, [k_n]=*Bc*$^{-1}$, T_k - the length of time equivalent code accumulated at the output of the integrator counters.

As we know from the above description of electric drive, ECU counters perform counting the number of pulses that is proportional to the difference between the reference period and current rotation of the rotor. Then, an overwriting of parallel codes of the counters from outputs of a digital-to-analog converters and expectations of the new interval counting pulses is performed. These operations are performed for a time equal to $T_u = \frac{4}{3}T_c$. The 4/3 ratio is obtained regarding the fact that the signal is given to the RPS, has a period three times smaller than the period of rotation of the rotor due to the fact that the latter has three pairs of poles. In addition, one signal period of RPS (equal to $T_c/3$) is used to rewrite the codes on the outputs of the counters in the RPS and the new expectations of interval counting pulses. During the time interval T_u supply the output voltage phases ECU does not change and is determined by code that was calculated at the previous interval T_u. Regarding the method of adjustment, given above at each successive time intervals T_u can get the following equation of electric:

$$\omega_{02} = k_d\left(1 - e^{-\frac{T_{u2}}{T_d}}\right)\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01} e^{-\frac{T_{u2}}{T_d}},$$

$$\omega_{01} = k_d\left(1 - e^{-\frac{T_{u1}}{T_d}}\right)\left(k_n (T_k + \Delta T) - \frac{T_d M_{on}}{k_d J}\right) + \omega_{02} e^{-\frac{T_{u1}}{T_d}},$$

$$\frac{2\pi}{T_2} = k_d\left(1 - e^{-\frac{T_2}{T_d}}\right)\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01} e^{-\frac{T_2}{T_d}},$$

$$\frac{2\pi}{T_2} = k_d\left(1 - e^{-\frac{T_1}{T_d}}\right)\left(k_n (T_k + \Delta T) - \frac{T_d M_{on}}{k_d J}\right) + \omega_{02} e^{-\frac{T_{u1}}{T_d}}, \qquad (11)$$

where $T_1 = T_e - \Delta T$, $T_2 = T_e - \Delta T$ - current periods of rotor at each successive time intervals T_{u1}, T_{u2}; ΔT - deviation from the reference current period, ω_{01}, ω_{02} - extreme values of angular velocities at the ends of time intervals T_{u1}, T_{u2}.

The first two equations (11) determine the value of the angular velocity at the edges intervals T_{u1}, T_{u2}, the other two equations (11) determine the value of the angular velocity at the edges intervals T_1, T_2, which are in the range T_{u1}, T_{u2}, and consistent with their seals, $\upsilon T_1 = T_{u1}$, $\upsilon T_2 = T_{u2}$ where the ratio $\upsilon > 1$ (in this device $\upsilon = \frac{4}{3}$. At standby mode, $T_1 \approx T_e$, $T_2 \approx T_e$, therefore $T_d >> T_{u1}$, $T_d >> T_{u2}$, $T_d >> T_1$, $T_d >> T_2$ and exponential function in equations (12) can be written as $e^{-\frac{T_{u1}}{T_d}} \approx 1 - \upsilon\frac{T_1}{T_d}$, $e^{-\frac{T_{u2}}{T_d}} \approx 1 - \upsilon\frac{T_2}{T_d}$, $e^{-\frac{T_1}{T_d}} \approx 1 - \frac{T_1}{T_d}$, $e^{-\frac{T_2}{T_d}} \approx 1 - \frac{T_2}{T_d}$.

Substituting the last expression in equation (11) and we receive

$$\omega_{02} = k_d \frac{\upsilon T_2}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01}\left(1 - \frac{\upsilon T_2}{T_d}\right),$$

$$\omega_{01} = k_d \frac{\upsilon T_1}{T_d}\left(k_n (T_k + \Delta T) - \frac{T_d M_{on}}{k_d J}\right) + \omega_{02}\left(1 - \frac{\upsilon T_1}{T_d}\right), \qquad (12)$$

$$\frac{2\pi}{T_2} = k_d \frac{T_2}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01}\left(1 - \frac{T_2}{T_d}\right),$$

$$\frac{2\pi}{T_2} = k_d \frac{T_1}{T_d}\left(k_n (T_k + \Delta T) - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01}\left(1 - \frac{T_1}{T_d}\right),$$

Substituting expressions $T_1 = T_e - \Delta T$, $T_2 = T_e - \Delta T$ in equations (11), we receive

$$\omega_{02} = k_d \frac{\upsilon T_e}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) +$$

$$+ k_d \frac{\upsilon \Delta T}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \omega_{01}\left(1 - \frac{\upsilon T_e}{T_d} - \frac{\upsilon \Delta T}{T_d}\right),$$

$$\omega_{01} = k_d \frac{\upsilon T_e}{T_d}\left(k_n\left(T_k + \Delta T\right) - \frac{T_d M_{on}}{k_d J}\right) -$$

$$- k_d \frac{\upsilon \Delta T}{T_d}\left(k_n\left(T_k + \Delta T\right) - \frac{T_d M_{on}}{k_d J}\right) +$$

$$+ \omega_{02}\left(1 - \frac{\upsilon T_e}{T_d} + \frac{\Delta T}{T_d}\right),$$

$$\frac{2\pi}{T_e + \Delta T} = k_d \frac{T_e + \Delta T}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) +$$

$$+ \omega_{01}\left(1 - \frac{T_e + \Delta T}{T_d}\right),$$

$$\frac{2\pi}{T_e - \Delta T} = k_d \frac{T_e - \Delta T}{T_d}\left(k_n\left(T_k + \Delta T\right) - \frac{T_d M_{on}}{k_d J}\right) +$$

$$+ \omega_{01}\left(1 - \frac{T_e - \Delta T}{T_d}\right). \tag{13}$$

Subtracting the second equation from the first (13), and then adding the second to the first of equations and following a number of transformations, we receive

$$\left(\omega_{02} - \omega_{01}\right)\left(2 - \frac{\upsilon T_e}{T_d}\right) = 2\frac{k_d}{T_d}\upsilon\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right)\Delta T -$$

$$- \frac{k_d k_n}{T_d}\upsilon T_e \Delta T + \frac{k_d k_n}{T_d}\upsilon \Delta T^2 - \left(\omega_{02} + \omega_{01}\right)\frac{\upsilon}{T_d}\Delta T, \tag{14}$$

$$\left(\omega_{02} + \omega_{01}\right)T_e = 2k_d T_e\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) +$$

$$+ k_d k_n T_e \Delta T - k_d k_n \Delta T^2 + \left(\omega_{02} - \omega_{01}\right)\Delta T.$$

Substituting expression for $\omega_{01} + \omega_{02}$ from another equations (14) into the first one, performing a series of transformations, we receive

$$\omega_{02} - \omega_{01} = \frac{k_d k_n \upsilon\left(\Delta T^2 - T_e^2\right)}{2T_e T_d + \upsilon\left(\Delta T^2 - T_e^2\right)}\Delta T\,. \tag{15}$$

Neglecting ΔT^2 relatively to equation T_e^2 ($T_e^2 >> \Delta T^2$) in expression (15), we receive

$$\omega_{01} - \omega_{02} \approx \frac{k_d k_n \upsilon T_e}{2T_d - \upsilon T_e}\Delta T\,. \tag{16}$$

Substituting expression (15) in the second equation (14), we have

$$\omega_{01} + \omega_{02} = 2k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + k_d k_n \Delta T -$$

$$- \frac{k_d k_n}{T_d}\Delta T^2 + \frac{k_d k_n \upsilon\left(\Delta T^2 - T_e^2\right)}{T_e\left[2T_d T_e + \upsilon\left(\Delta T^2 - T_e^2\right)\right]}\Delta T^2. \tag{17}$$

Neglecting members ΔT^2 in the last equation, we receive

$$\omega_{01} + \omega_{02} \approx 2k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + k_d k_n \Delta T. \tag{18}$$

Expression (18) is written as

$$0{,}5\left(\omega_{01} + \omega_{02}\right) \approx k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + 0{,}5 k_d k_n \Delta T. \tag{19}$$

Thus we have the expression for the fluctuations magnitude of the angular velocity of the rotor (15), (16) and the mean angular velocity of the rotor (19).

Then we have to find the difference of the third and fourth equations (13) and we receive

$$\frac{2\pi\left(T_e - \Delta T\right) - 2\pi\left(T_e + \Delta T\right)}{T_e^2 - \Delta T^2} = \frac{2k_d}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right)\Delta T -$$

$$- \frac{k_d k_n T_e}{T_d}\Delta T + \left(1 - \frac{T_e}{T_d}\right)\left(\omega_{01} - \omega_{02}\right) -$$

$$- \left(\omega_{01} + \omega_{02}\right)\frac{\Delta T}{T_d} + \frac{k_d k_n}{T_d}\Delta T^2.$$

Substituting the last expression difference value $\omega_{01} - \omega_{02}$ and amounts $\omega_{01} + \omega_{02}$ the expressions (15), (17). We receive

$$\frac{2\pi \Delta T}{\Delta T^2 - T_e^2} = \frac{2k_d}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right)\Delta T -$$

$$- \frac{k_d k_n T_e}{T_d}\Delta T + \left(1 - \frac{T_e}{T_d}\right)\frac{k_d k_n \upsilon\left(\Delta T^2 - T_e^2\right)}{2T_d T_e + \upsilon\left(\Delta T^2 - T_e^2\right)}\Delta T -$$

$$- \left\{2k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + k_d k_n \Delta T -\right.$$

$$\left. - \frac{k_d k_n}{T_e}\Delta T^2 + \frac{k_d k_n \upsilon\left(\Delta T^2 - T_e^2\right)\Delta T^2}{T_e\left[2T_d T_e + \upsilon\left(\Delta T^2 - T_e^2\right)\right]}\right\}\frac{\Delta T}{T_d} +$$

$$+ \frac{k_d k_n}{T_d}\Delta T^2.$$

Reducing $\Delta T \neq 0$, neglecting members with ΔT^4 and making some transformations, we obtain

$$\frac{4\pi}{\Delta T^2 - T_e^2} = \frac{k_d k_n\left(\Delta T^2 - T_e^2\right)}{T_d T_e} + \frac{k_d k_n \upsilon\left(\Delta T^2 - T_e^2\right)}{2T_d T_e + \upsilon\left(\Delta T^2 - T_e^2\right)} +$$

$$+ \frac{k_d k_n \upsilon T_e^3}{T_d\left[2T_d T_e + \upsilon\left(\Delta T^2 - T_e^2\right)\right]}. \tag{20}$$

Expression (20) can be represented as the equation of the third degree relative value $\Delta T^2 - T_e^2$, namely

$$\frac{k_d k_n \upsilon}{T_d T_e}\left(\Delta T^2 - T_e^2\right)^3 + k_d k_n (2+\upsilon)\left(\Delta T^2 - T_e^2\right)^2 + + \frac{k_d k_n \upsilon T_e^2 - 4\pi\upsilon T_d}{T_d}\left(\Delta T^2 - T_e^2\right) - 8\pi T_d T_e = 0. \quad (21)$$

Given the above numerical values included in the expression (21), may be rewritten into the following equation

$$k_d k_n (2+\upsilon)\left(\Delta T^2 - T_e^2\right)^2 + + 4\pi\upsilon\left(\Delta T^2 - T_e^2\right) - 8\pi T_e T_d = 0. \quad (22)$$

Let's solve (22) relative value $T_e^2 - \Delta T^2$. We obtain

$$T_e^2 - \Delta T^2 = \frac{-2\pi\upsilon \pm \sqrt{4\pi^2\upsilon^2 + 8\pi T_e T_d k_d k_n (2+\upsilon)}}{k_d k_n (2+\upsilon)}.$$

From which we obtain

$$\Delta T^2 = T_e^2 + \frac{2\pi\upsilon}{k_d k_n (2+\upsilon)} \pm \sqrt{\frac{4\pi^2\upsilon^2}{k_d^2 k_n^2 (2+\upsilon)} + \frac{8\pi T_e T_d}{k_d k_n (2+\upsilon)}}. \quad (23)$$

Another expression that follows from (23), namely

$$\Delta T^2 = T_e^2 + \frac{2\pi\upsilon}{k_d k_n (2+\upsilon)} + \sqrt{\frac{4\pi^2\upsilon^2}{k_d^2 k_n^2 (2+\upsilon)} + \frac{8\pi T_e T_d}{k_d k_n (2+\upsilon)}} \quad (24)$$

can be neglected because the value ΔT^2 during normal operation should be less than T_e^2.

Next, we add the third of equations (13) to the fourth. We obtain

$$\frac{2\pi(T_e - \Delta T) + 2\pi(T_e + \Delta T)}{T_e^2 - \Delta T^2} = \frac{2k_d T_e}{T_d}\left[k_n T_k - \frac{T_d M_{on}}{k_d J}\right] + + \frac{k_d k_n T_e}{T_d}\Delta T + (\omega_{01} + \omega_{02})\left(1 - \frac{T_e}{T_d}\right) + + (\omega_{01} - \omega_{02})\frac{\Delta T}{T_d} - \frac{k_d k_n}{T_d}\Delta T^2. \quad (25)$$

Substituting in this equation the above expressions (16) and (18) we obtain

$$\frac{4\pi T_e}{T_e^2 - \Delta T^2} = \frac{2k_d T_e}{T_d}\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \frac{k_d k_n T_e}{T_d}\Delta T + + 2\left(1 - \frac{T_e}{T_d}\right)k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + \left(1 - \frac{T_e}{T_d}\right)k_d k_n \Delta T - - \frac{k_d k_n \upsilon T_e}{T_d (2T_d - \upsilon T_e)}\Delta T^2 - \frac{k_d k_n}{T_d}\Delta T^2. \quad (26)$$

Neglecting members of the ΔT^2 in equation (26), we will obtain

$$\frac{4\pi}{T_e} \approx 2k_d\left(k_n T_k - \frac{T_d M_{on}}{k_d J}\right) + k_d k_n \Delta T. \quad (27)$$

Comparing the expressions (18) and (27) up to a small size ΔT^2, following equation can be written

$$\omega_{01} + \omega_{02} \approx \frac{4\pi}{T_e}. \quad (28)$$

From the expression (16) it follows that the $\Delta T = 0$ $\omega_{01} = \omega_{02}$ i.e. the established mentioned angular velocity is $\frac{2\pi}{T_e}$.

Measuring the difference between the reference periods and the fluid is done by completing the last pulse frequency of 20 *MHz* and counting the number of pulses. The value ΔT with discrete quantized $\delta_T = 0{,}5\cdot 10^{-7}\,s$. The law of distribution δ_T is even [11] because average quarter deviation of this value is $\sigma_T = \frac{\delta_T}{2\sqrt{3}}$, $\sigma_T = 0{,}144\cdot 10^{-7}\,s$. In admission to the difference $0{,}5\cdot 10^{-6}\,s$ periods such value is acceptable.

Conclusions. The developed electric drive valve engine of direct current analog-to-digital loop control allows the following:

Simplify the design of gimbals (last item removed from the dynamic configuration, i.e. threaded holes, adjusting screws, glue connections for fixing screws)

Simplify the process of dynamic adjustment of gravimeter (required conversion factor reference period of discrete reference period generator rotor with adjustable conversion factor of this period, and rewelded jumper by which a binary code corresponding calculated factor is installed, is calculated).

Further studies allow assessing the increasing accuracy of dynamic settings of gravimeter.

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