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IMPROVING A TECHNIQUE FOR THE ESTIMATION AND ADJUSTMENT OF COUNTERBALANCE OF SUCKER-ROD PUMPING UNITS' DRIVES

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З метою зменшення впливу нерівномірності навантаження на роботу приводів штангових свердловинних насосних установок за результатами проведених досліджень запропоновано вдосконалений спосіб оцінки та коректування зрівноваження. Спосіб передбачає визначення необхідного положення кривошипних противаг на основі залежностей зміни активної потужності та швидкості обертання вала двигуна. Експериментальні дослідження для отримання згаданих залежностей проведені за допомогою портативного інформаційно-вимірювального комплексу. Його робота ґрунтується на технології віртуальних приладів, методах цифрової обробки сигналів і графічному програмуванні алгоритмів прикладних програм. Відповідно до пропонованого способу оптимальне місце розташування кривошипних противаг визначається з умови рівності максимумів зведеного крутного моменту на вихідному валу редуктора. При цьому графік зміни моменту сил корисного опору є різницею зведеного крутного момент на вихідному валу редуктора, отриманого за результатами досліджень, і моменту від кривошипа та противаг. Можливість використання вдосконаленого способу для коректування зрівноваженості приводів із достатньою для цього точністю підтверджено результатами повторного ватметрування, виконаного після зміни положення кривошипних вантажів відповідно до сформованих рекомендацій. Обґрунтовано, що достатня точність контрольованих для реалізації способу параметрів досягається за умови забезпечення кута повороту кривошипа між точками вимірювання від 5° до 1°. Впровадження способу дозволяє мінімізувати затрати часу на реалізацію процесу зрівноваження та забезпечити зниження впливу нерівномірності навантаження на роботу приводу

Ключові слова: верстат-качалка, оцінка зрівноваження, ватметрограма, крутний момент кривошипа, дискретність вимірювання

1. Introduction

A pumping unit is a component of the sucker-rod pumping unit (SRPU), which is connected by a string of pumping rods to the plunger of the pump. A string of rods, given its considerable length and complex profile of a well, is exposed to the action of static and dynamic loads associated with the forced, free, parametric, and frictional oscillations [1].

It is obvious that these loads are transmitted also to the SRPU drive's elements. Teeth of the gearboxes toothed wheels, which are components of the mechanisms designed to reduce motor shaft rotation speed to the number of balancer swings, are exposed during operation to the action of loads that vary over time in line with a pulsating cycle. In this case, the level of maximal loads on individual teeth is different; it is defined by patterns in the drive operation and the degree of its equilibration. Another characteristic feature is a change in the load that acts not only on a tooth of the reduction gear, but on all its elements. As a result, under actual conditions, there are quite often observed failures of equipment, which is also predetermined by susceptibility of the drive nodes to the adverse effect of the environment, by defects in installation and maintenance [2]. Therefore, reducing the impact of uneven load on operation of BRPU drives is an important issue; it is a relevant task to study how that can be achieved, specifically by means of proper equilibration.

2. Literature review and problem statement

A string of rods over a cycle of the beam swing undergoes two transient processes associated with the displacement of a polished rod and an increase or decrease in static loads. The transient processes represent free oscillations of a string of rods whose amplitude depends on the forcing effort and the natural frequency. Therefore, the level of dynamic loads is predetermined by the parameters of an individual well and the equipment used; it changes, relative to the total loads that act at the point of rods suspension (polished rod load), over a wide range. There are wells for which dynamic loads are proportionate and even significantly exceed the static ones, which is due to the weight of a column of fluid above the plunger.

One of the ways to reduce the oscillations of a string of rods, and, therefore, the non-uniformity in the drive load, is the application of elastic suspensions and shock absorbers [3, 4]. Analytical and numerical-analytical research into operational properties of elastic elements in such devices are reported in paper [5]. However, those shock absorbers whose parameters are selected for a certain level of loading cease to be effective when it is changed. A slight change in frequency or parameters for a damped object could lead to a dangerous increase in the amplitude of oscillations.

Another technique to reduce dynamic loads is to increase the length of the rod run and to decrease the number of beam swings [6]. The slower the forcing effort is applied, the lower the level of dynamic loads. However, the speed of its application is limited by the structural features of controlling elements in drives. Thus, the dimensional range of beam pumping units does not provide for the length of the run above 3–3.5 m. Application of the long-stroke pumping units, especially in fields that are at a later stage of operation, is economically impractical.

Reducing the impact of uneven load on the operation, particularly, of reduction gears, V-belt drives, and electric motors, is achieved by the high-quality execution of the drive balance. Owing to this, the beam pumping unit with proper equilibration ensures the least mean square value of power over a complete cycle of its operation [7].

At present, most of the deposits in the western region are at the final stage of development, which is characterized by a significant decrease in the productivity of wells. This has led to a decrease in the diameters of downhole pumps, in the number of beam swings, as well as in the run length of the rod's suspension point (polished rod). However, the vast majority of wells operate SRPU with the drives whose basic parameters were appropriate during the period of early development of deposits oilfield. In this case, the power of drives is enough to work in a highly unbalanced state. The vast majority of beam pumping unit are overbalanced, while balancing according to the recommended nomograms is impossible.

Such a state is necessarily accompanied by periodic thud in the reduction gear, which is a consequence of change in the direction of action of circular force in a toothed gear. This change is characteristic of both stages in a reduction gear, it is accompanied by shock loads, and predetermines the occurrence of vibrations, which leads to a series of faults.

At the same time, it should be noted that balanced is typically performed by oil and gas services departments (NGVU) via control over the magnitude of current in the windings of the induction motor stator. However, given a large underload of prime motors, the efficiency of balancing the beam pumping units based on operating currents is low.

It should be also noted that the most common technique for domestic NGVU to acquire diagnostic information implies the are monitored by measuring the load on the polished rod with dynamometer. This method is widely known throughout the world and is employed for both qualitative and quantitative estimation of equipment operating conditions [8, 9]. This is due to the fact that the load on a polished rod is defined both by the parameters of a pumping unit and its operation mode and the condition of separate assemblies in subsurface equipment. The measurement with dynamometer is not informative regarding the load applied directly to the drive elements that are intended to reduce the rotation speed of motor shaft to the number of beam swings, specifically, the reduction gear and the V-belt drive.

In the classical theory of mechanisms and machines, the mechanism is considered to be balanced if the sum of external, internal forces, and the forces of inertia, as well as moments of forces, equals zero [10]. Regarding the drives in SRPU, external force is the load that acts at the point of rods' suspension (polished rod). Its equilibration, under actual conditions, is ensured by the arrangement of additional masses (counterweights) at a crank or at the walking beam of a pumping unit. In this case, external forces are cumulative to the crank, while the action is equivalent to the summary torque that acts at the output shaft of the reduction gear. Given this, the main method for determining the equilibration is an estimation of the dependence of momentum on the angle of rotation over one cycle of change in load.

It is very difficult to acquire a torque diagram by direct measurement. This is due to the structural features of the crank, which hosts a node that joins the connecting rod. That is why it is derived via calculation involving a diagram for a change in the load at the point of rods' suspension and taking into consideration the links in the controlling mechanism, the decisive ones among which are the mass of cranks and the counterweights placed on them [11]. The specified method makes it possible to estimate the counterbalance and to determine the required place to position the counterweights; it, however, requires the necessary consideration of the kinematics of the controlling element in a beam pumping unit with specific dimensions.

According to [12], it is the wattmeter measurement that is a more precise method for estimating the equilibration of a pumping unit, because it rules out the need to calculate the kinematic parameters. In this case, a coefficient of unbalancing is determined from:

$$K_H = \frac{P_{up}^{\max} - P_{down}^{\max}}{P_{up}^{\max} + P_{down}^{\max}} \cdot 100\,\%, \qquad (1)$$

where $P_{up}^{\max}$, $P_{down}^{\max}$ are the maximum values for power when a point of rods' suspension moves up and down. A pumping unit is considered unbalanced if the value for a coefficient exceeds 5 %.

There are also such controllers, which, after several measurements of consumed power accompanied by a change in the position of crank counterweights, produce recommendations for optimal arrangement [13]. However, in this case, there is a need to repeatedly displace the loads.

Regarding the process of wattmeter measurement, it should be noted that the diagrams of load changes are acquired through the registration of instantaneous values for consumed power [14, 15]. Existing technical means ensure high measurement discreteness. Owing to this, such values for power are registered that correspond to the loads predetermined by various oscillatory processes. However, the issue that remains unexplored is the impact of measurement discreteness on the estimation of drive counterbalance.

3. The aim and objectives of the study

The aim of this study is to improve a technique for the estimation and adjustment of equilibration of sucker-rod pumping units based on a wattmeter measurement method.

To accomplish the aim, the following tasks have been set:

– to substantiate basic principles for determining the required position of crank counterweights based on the results of wattmeter measurement;

– to conduct experimental research in order to obtain initial information for the estimation of balance of the drive and to verify recommendations regarding the adjustment of balance;

– to establish acceptable discreteness in measuring controlled parameters over time in order to implement the technique.

4. Substantiation of basic principles for the implementation of the technique for determining the position of crank counterweights

In order to reduce the cost of execution of operations regarding the equilibration of SRPU drive, we propose an improved technique for determining the required position of crank counterweights based on the results of wattmeter measurement.

The momentum of a crank shaft is linked to the momentum on the electric motor shaft via relation:

$$M_{cr} = M_{mo} \cdot u_{belt} \cdot u_{red} \cdot \eta_{belt} \cdot \eta_{red}, \qquad (2)$$

where M_{cr}, N·m is the torque acting on the shaft of the electric motor; u_{belt}, u_{red} is the gear ratio of a belt transmission and reduction gear; η_{belt}, η_{red} is the efficiency of a belt transmission and reduction gear.

The momentum on the shaft of the electric motor is determined based on the values for power and rotation speed of the shaft:

$$M_{mo} = \frac{30 \cdot P_{mo}}{\pi \cdot n_{mo}}, \qquad (3)$$

where P_{mo}, n_{mo} is the output power, W and rotation speed, rot/min of prime motor.

The cumulative torque acting at the output shaft of the reduction gear is then determined from:

$$M_{cr} = \frac{30 \cdot P_{mo}}{\pi \cdot n_{mo}} \cdot u_{belt} \cdot u_{red} \cdot \eta_{belt} \cdot \eta_{red}. \qquad (4)$$

The next step is the calculation of the momentum created by cranks and counterweights placed on them:

$$M_{CB} = G_{cw1} \cdot l_{cw1} \cdot \cos(\varphi_1 + \beta_1) + {}$$
$$+ G_{cw2} \cdot l_{cw2} \cdot \cos(\varphi_1 - \beta_2) + G_{cr} \cdot \frac{r_{cr}}{2} \cdot \cos(\varphi_1), \qquad (5)$$

where G_{cw1}, G_{cw2} is the weight, N of counterweights that are placed on cranks; l_{cw1}, l_{cw2} are the distances, m to the position of centers of counterweights' masses; j_1 is the rotation angle of the crank; β_1, β_2 are the angles of position of the centers of mass of crank counterweights; G_{cr}, r_{cr} is the weight of the crank, N and the distance to its center of mass, m respectively (Fig. 1).

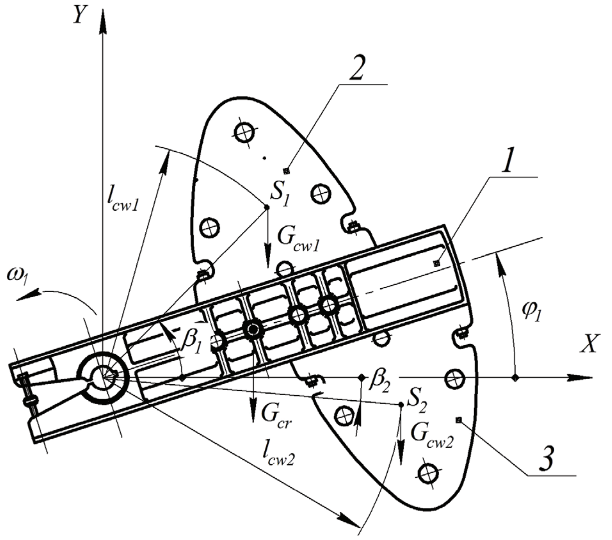

Fig. 1. Estimation scheme for determining the momentum created by crank 1 and by counterweights 2 and 3 mounted onto it

We acquire a diagram of the momentum, cumulative to the crank, due to the force of useful resistance applied at the point of rods' suspension rods, as the difference between the momentum determined from (4) and the momentum from the crank and counterweights (5). The optimal location of crank counterweights is determined based on the resulting diagram from the condition for equality between maxima of the cumulative torque at the output shaft of the reduction gear for the upward and downward motion of rods.

5. Results of experimental research into counterbalance of the drive and verification of recommendations for adjustment

Experimental research into active power and rotation speed of the shaft in the drive induction electric motor for a beam pumping unit was carried out using the mobile information-measuring complex [16]. Underlying its operation is the technology of virtual instruments based on methods for digital signal processing and graphical programming of algorithms for applied software [17].

In this case, we measured actual values of voltage and phase current of the electric motor employing an analog-to-digital conversion and calculating the root-mean-square value:

$$U=\sqrt{\frac{1}{T}\int_{0}^{T}u(t)\mathrm{d}t}; \qquad (6)$$

$$I=\sqrt{\frac{1}{T}\int_{0}^{T}i(t)\mathrm{d}t}, \qquad (7)$$

where $u(t)$, $i(t)$ are the instantaneous values for voltage and current, T is the period of integration.

The active power of the electric motor phases is computed by averaging the value of instantaneous power over the period:

$$P=\frac{1}{T}\int_{0}^{T}p(t)\mathrm{d}t, \qquad (8)$$

where $p(t)$ is the instantaneous power value.

The active power of electric motor was obtained from summing the active powers in its phases in accordance with the principle of a three-wattmeter circuit.

Experimental research aimed at acquiring the wattmeter diagram and the estimate of equilibration for the SRPU drive was carried out at a well operated under a permanent mode and equipped with the beam pumping unit UP12-T-55. The result of mathematical processing of recorded signals is the file that contains the measured voltage, current, active power, the speed of shaft rotation, and the mark that corresponds to the extreme upper position of the well rod's suspension. In this case, the resolution of measurement of the above-specified parameters can be assigned in a range from 1 to 50 points per second.

Based on the results of our study, we constructed a diagram of change in the motor's active power over one rotation of the crank in a beam pumping unit (Fig. 2).

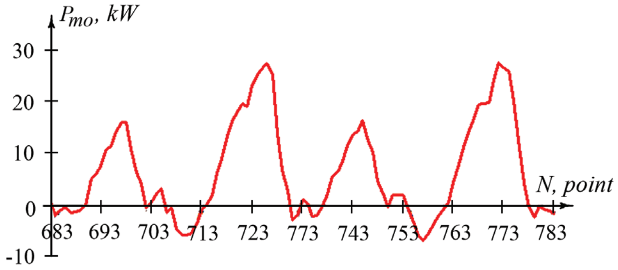

Fig. 2. Diagram of the recorded active power of the motor over one rotation of the crank in a beam pumping unit

Based on the values, defined experimentally for active power and the rotation speed of the electric motor's shaft according to dependence (4), we derived a diagram of change in the torque at the output shaft of the reduction gear (Fig. 3).

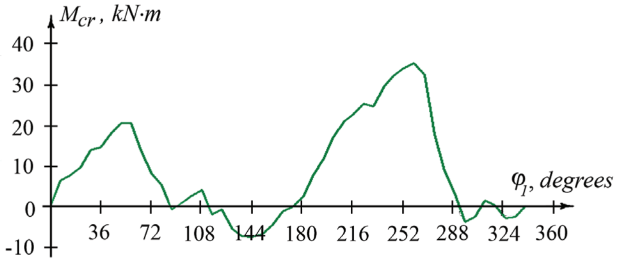

Fig. 3. Diagram of change in the torque at the output shaft of the reduction gear over one rotation of the crank

The diagram of the momentum, reduced to the crank, created by the force of useful resistance acting at the point of rods' suspension, is constructed as the difference between the resultant momentum and the momentum from crank counterweights (Fig. 4).

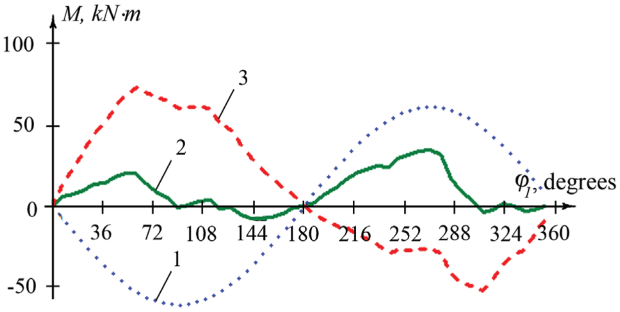

Fig. 4. Diagrams of change in momenta:
1 — the moment created by the crank and the counterweights mounted unto it; 2 — the cumulative torque that acts at the output shaft of the reduction gear; 3 — the moment created by the force of useful resistance that acts at the point of rods' suspension

The optimal position for the crank counterweights is determined based on the constructed diagram for the momentum created by the force of useful resistance that acts at the point of rods' suspension from the condition for equality of maxima in the cumulative torque. A diagram of change in the estimated cumulative momentum, predicted after the counterweight displacement, at the output shaft of the reduction gear is shown in Fig. 5.

Upon performing the equilibration taking into consideration the recommendations devised on the basis of our research, we measured the active power whose diagram is shown in Fig. 6. Under the specified conditions, the maximum values for power required to move upwards and downwards amounted to, respectively, 20.6 and 22.1 kW. The minimum negative value of power at the end of the move upwards was –4 kW.

Thus, based on the obtained results, we registered a decrease in the coefficient of non-equilibration to 3.5 %, which, according to [12], allows us to consider the beam pumping unit to be balanced.

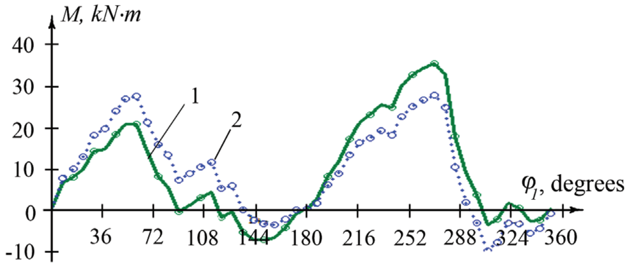

Fig. 5. Diagrams of change in the cumulative momentum at the output shaft of the reduction gear: 1 — for the unbalanced beam pumping unit; 2 — predicted after the equilibration of a beam pumping unit by displacing a load over a recommended distance

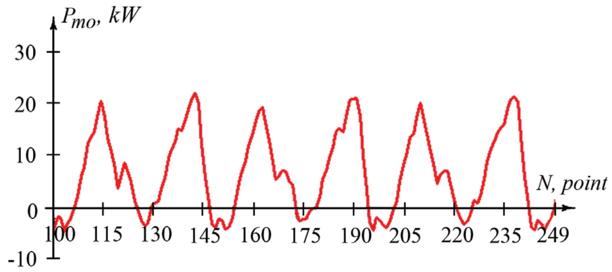

Fig. 6. A diagram of the recorded active power of motor over three rotations of the crank in a beam pumping unit after performing the equilibration

6. Discussion of research results and determining the required discreteness in measurements

The equipment, used in the course of our experiment, allows the measurement of power at time discreteness of up to 100 measurements per second. That is why it is necessary to set the optimum discreteness for signal registration in terms of time. Fig. 7 shows diagrams of the recorded power of drive motor in the beam pumping unit UP12-T-55, acquired at the well of the largest Ukrainian oil and gas company PAT «Ukrnafta» («Nadvirnanaftogaz» NGVU) for different discreteness between signal counts over time.

As decrease in the time intervals between measurements in a range from 1 to 0.02 seconds affects the shape of the diagram; starting at discreteness 25 point/s, the stochastic component of the signal considerably complicates the analysis of processes of change in power.

Values for the coefficient of non-equilibration for these cases are given in Table 1. Note that when measuring the signal with a frequency of 1 point/s (Fig. 7, *a*) the maximum values for power during the upward and downward motion of rods are not cyclically recurring.

For example, at the specified accuracy for the range from points 13 to 23 we obtained values for the maxima of power – 11.79 and 25 kW. At the same time, for the range from points 23 to 33 we registered the values of 13.35 and 21.38 kW, respectively. That should indicate the non-recurrence of the process of change in power.

However, when increasing the number of points to 5 per second (Fig. 7, *b*), we obtained a cyclically repeated process with maximum values that are, respectively, 15.82 kW for the upward motion, and 27.13 kW for the rods' downward motion.

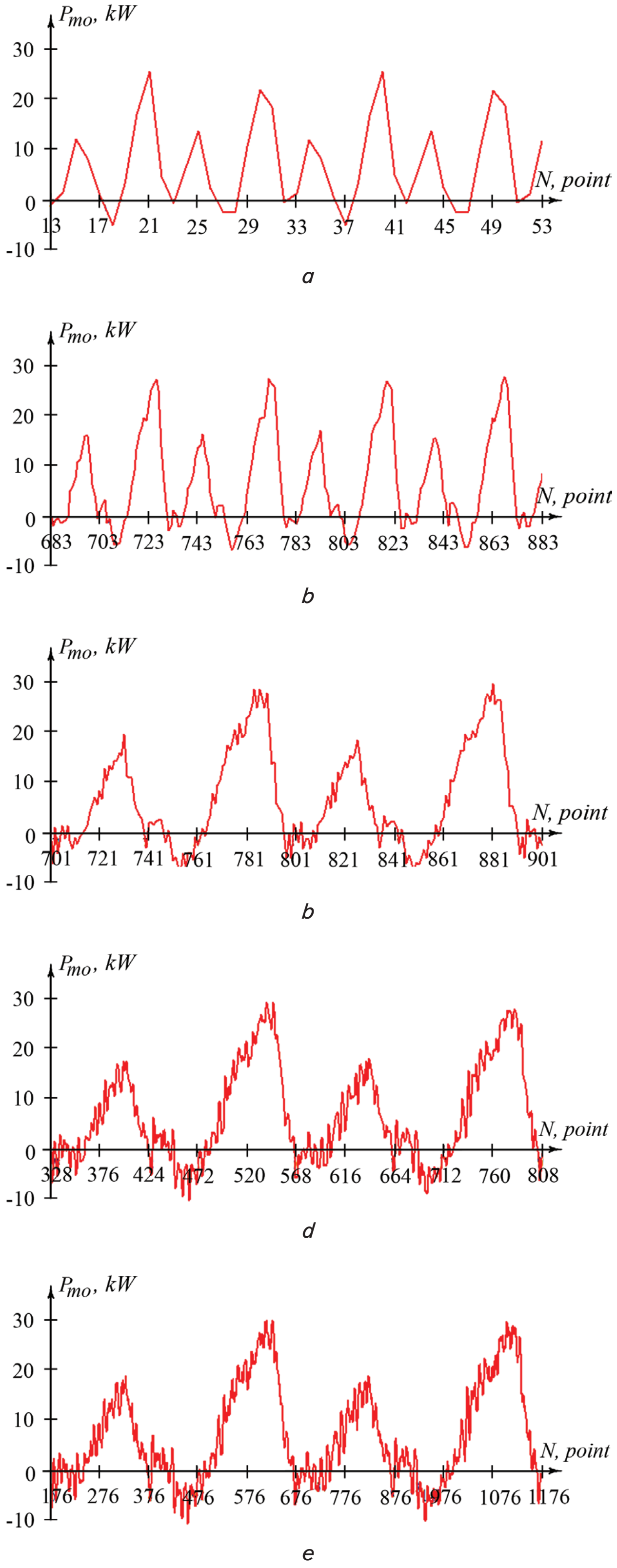

Fig. 7. Diagrams of power, acquired at varying discreteness: *a* — 1 point per second; *b* — 5 points per second; *c* — 10 points per second; *d* — 25 points per second; *e* — 50 points per second

In addition, while analyzing the research results, values for the coefficients of non-equilibration were determined based on the diagram of change in active power during a single rotation of the crank. In this case, a cycle of loading was chosen randomly. Next, in order to compare, we derived coefficients K_H based on the average value for the maxima of power over 5 rotations of the crank (given in the last column).

Table 1

Comparison of measurements at different discreteness of points

Discreteness, points/s	$P_{up}^{\max}$, kW	$P_{down}^{\max}$, kW	K_H, %	K_H, % over 5 rotations
1 (range of points 13–23)	11.79	25	–35.9	–31.3
1 (range of points 23–33)	13.36	21.38	–23.1	
5	15.82	27.13	–26.3	–25.4
10	18.06	28.37	–22.2	–22.53
25	17.4	27.57	–22.6	–22.3
50	17.93	27.7	–21.4	–22.5

In the theory of mechanisms and machines, it is accepted to run an analysis of change in the mechanical characteristic, specifically rotating momentum, work, kinetic energy, power, etc., at a step in the rotation angle of the crank not exceeding 30° [10].

When measuring the power, frequency of the crank rotation in a pumpjack was 6.5 rpm, that is, over 1 second the crank of a beam pumping unit rotated at angle 39°, which exceeded the maximally permissible value. That is why the coefficient of the crank rotation non-uniformity, determined at different ranges of points (13–23 and 23–33), is characterized by a substantial discrepancy. The closest values for K_H both for the random values and those averaged over 5 rotations are accepted at discreteness 10, 25, and 50 points/s. In this case, the angle of crank rotation between the points is, accordingly, 3.9°, 1.56°, and 0.78°.

Thus, in order to obtain reliable information, the crank angle of rotation between the points of measurement should be from 5° to 1°. Since rotation frequency of the crank in a beam pumping unit could be different, the required discreteness in signal is appropriately determined from:

$$i = \frac{6 \cdot n_{cr}}{\Delta\varphi}, \tag{9}$$

where n_{cr}, r/min is the number of crank rotations; $\Delta\varphi$, degrees is the angle of crank rotation.

An analysis of results of wattmeter measurement following the adjustment of counterbalance revealed similar dependences of measurement accuracy on their discreteness.

The drawbacks of this study include the application, in determining the cumulative torque that acts at the output shaft of the reduction gear, of actual values for the frequency of rotation of the motor shaft, rather than the crank directly. This prevented taking into consideration a possible impact on the diagram of change in the torque that exerts the sliding of the belt transmission. Further studies could address resolving the issue on the direct determining of the actual speed of crank rotation.

It should also be noted that our research relates to the continuous operation mode of a well. Under a periodic operation, one observes a fall in the level of fluid in the space beyond the pipes, which leads to an increase in static loads and, therefore, in the forcing effort, which affects the level of dynamic loads. This predetermines a change in the level of total loads at a point of rods' suspension during the period of equipment operation. That is why the counterbalancing process under such conditions will be different from the counterbalancing of the permanently working drive. Special attention should be paid to analysis of dependences of change in the active motor power during operation of SRPU and to the substantiation of initial parameters in order to devise recommendations on the adjustment of counterbaancing.

7. Conclusions

1. We have constructed an improved technique for the estimation and adjustment of equilibration of SRPU drive based on the dependences of change in the active power and rotation speed of the motor shaft over time. They are the base for constructing a diagram of change in the torque at the output shaft of the reduction gear and for subsequent separation of the component predetermined by the forces of useful resistance. Determining the optimum location of crank counterweights based on the constructed diagram from the condition for equality of maxima of the torque reduced to the crank is easy to implement and requires no consideration of the kinematics of the controlling element in a beam pumping unit.

2. We have experimentally verified the proposed technique for the estimation and adjustment of counterbalancing of SRPU drive, whose unbalancing coefficient, determined based on the results of initial wattmeter measurement, was 22 %. Following the adjustment of counterbalancing according to the recommendations, devised by applying the improved technique, the unbalancing coefficients decreased to 3.5 %. Thus, one could argue that the resulting value for the coefficient complies with existing requirements, and the drive counterbalancing was conducted with a sufficient accuracy.

3. It was established in the course of an analysis of research results that the discreteness of measurement of controlled parameters over time must be in the range that corresponds to the angle of crank rotation, from 1° to 5°. Measuring controlled parameters with insufficient frequency (1 point/sec) leads to significant errors when determining a coefficient of unbalancing. An increase in discreteness above 25 points per second has almost no effect on the accuracy of determining a coefficient of unbalancing; however, a stochastic signal component considerably complicates analysis of processes of change in power.

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