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Estimation of the equality of the beamless sucker-rod oil pumping unit by the value of the consumption current

Oszacowanie wyważenia zespołu pomp żerdziowych bez żurawia na podstawie wartości zużywanego prądu

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ABSTRACT: The article presents the results of experimental studies to assess the loading and balancing of a new constructive solution of beamless sucker-rod pumping units. It is noted that the key factor that has the most significant effect on the mean time between failures (MTBF) is the right balancing of the pumping unit. The main purpose of the balancing device is the accumulation of potential energy during the downstroke and its release during the upstroke of the rod. It has been proved that the proposed additional balancing system (movable counterweight) which helps to reduce the uneven load on the electric motor and the power consumption of the pumping unit will also increase the efficiency of the beamless sucker-rod pumping unit. It was found that losses in sucker-rod pumps depend on the degree of balance of the counterweights. If the unbalance coefficient of the equipment is in the range from –5 to +5%, then the power loss due to unbalance can be ignored. In the current article, the authors propose a technique that allows to determine the energy characteristics of the electric drive of the pumping unit under conditions of a cyclically changing load and insufficient balance. It was revealed that when the balancer head passes from the upstroke to the downstroke and vice versa, there are sections with a negative value of the torque, which is explained by the influence of the inertial forces of the moving masses. This leads to shocks in the gearing of the reducer at the extreme positions of the cranks, increased wear and possibly to breakage of the teeth. Since it is not possible to completely eliminate this phenomenon, one should strive to limit the value of the negative torque by the correct balancing of the sucker-rod pump. In all cases, the change in the operating mode of a new constructive solution of beamless pumping unit requires new calculations, and requires changing the position and weights of movable and rotary counterweights (with combined balancing).

Key words: mechanical drive of sucker-rod pumps, sucker rod pumping unit, rocking machine, transforming mechanism, balancing, movable counterweight, cyclic load, rod suspension point, beamless, engine, gearbox, microcontroller.

STRESZCZENIE: W artykule przedstawiono wyniki badań eksperymentalnych dotyczących oceny obciążenia i wyważania nowego rozwiązania konstrukcyjnego zespołów pomp żerdziowych bez żurawia. Należy zauważyć, że kluczowym czynnikiem, mającym największy wpływ na średni czas pomiędzy awariami (MTBF), jest właściwe wyważenie zespołu pompowego. Głównym celem urządzenia do wyważania jest akumulacja energii potencjalnej podczas ruchu żerdzi w dół i jej uwolnienie podczas jej ruchu w górę. Udowodniono, że proponowany dodatkowy system wyważania (przesuwna przeciwwaga), który pomaga zmniejszyć nierównomierne obciążenie silnika elektrycznego i pobór mocy zespołu pompowego, zwiększy również wydajność zespołu pompy żerdziowej bez żurawia. Stwierdzono, że straty mocy żerdziowych pomp ssących zależą od stopnia wyważenia przeciwwag. Straty mocy spowodowane niewyważeniem mogą zostać zignorowane, jeżeli współczynnik niewyważenia urządzenia mieści się w zakresie od −5% do +5%. W niniejszym artykule autorzy proponują technikę pozwalającą na wyznaczenie charakterystyk energetycznych napędu elektrycznego zespołu pompowego w warunkach cyklicznie zmieniającego się obciążenia i niedostatecznego wyważenia. Okazało się, że kiedy głowica wyrównywacza przechodzi z ruchu w górę do ruchu w dół i odwrotnie, to występują odcinki z ujemną wartością momentu obrotowego, co wytłumaczono wpływem sił bezwładności poruszających się ciężarów. W skrajnych położeniach korb prowadzi to do wstrząsów w przekładni redukcyjnej, zwiększonego zużycia, a nawet do wyłamania zębów. Ponieważ nie jest możliwe całkowite wyeliminowanie tego zjawiska, należy dążyć do ograniczenia wartości ujemnego momentu obrotowego poprzez prawidłowe wyważenie pompy żerdziowej. We wszystkich przypadkach zmiana trybu pracy nowego rozwiązania konstrukcyjnego zespołu pompowego bez żurawia wymaga przeprowadzenia nowych obliczeń oraz zmiany położenia i masy przesuwnych i obrotowych przeciwwag (z wyważeniem łączonym).

Słowa kluczowe: mechaniczny napęd pomp żerdziowych, zespół pompy żerdziowej, kiwon, mechanizm przekształcający, wyważanie, przesuwna przeciwwaga, cykliczne obciążenie, punkt zawieszenia żerdzi, bez żurawia, silnik, skrzynia biegów, mikrokontroler.

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Introduction

At present, mechanised oil production by sucker rod pump installations is the main and most widespread method of the operation of oil wells. Mechanised oil production is the most energy-intensive process, which consumes 56.7% of electricity (Zhivaeva et al., 2016). Specific energy consumption of a sucker rod pumping unit is on average 10 kW/h per 1 ton of fluid lifted from the well (Khakimyanov, 2014). Taking into account the equipping of most wells with the sucker rod pumping units, increasing their efficiency is becoming one of the priority tasks of oil producing companies. Currently, various sucker rod pumping units are applied for the mechanised operation of oil wells. Among of the existing mechanised methods of oil production, the most common is sucker rod pumping with individual balancing drives – the so-called pumping units (Ivanovsky et al., 2002; Mishchenko, 2003; Arbuzov, 2011). One of the most important components of sucker rod pumping units – the mechanical drive – is located on the surface of the earth, over the exploited wells. There is a wide variety of designs for sucker rod pump drives. Pumping units are an indispensable technique in the oil industry. In most modern pumping units as a transforming mechanism using four-bar slider-crank linkage with a two-arm balancer, the characteristics and parameters of the drive depend on the ratio of the dimensions of the links (Ishmurzin, 2013). The mechanical drive provides movement of the pump plunger by means of the sucker rod's column. This type of pumping unit is the most widespread in the oil industry, and at present more than half of operating wells are equipped with them. The ground part of the pumping unit – the rocking machine – is fairly conservative equipment whose structural elements have remained unchanged for a long time.

However, despite all the reliability of the device, beam-pumping unit have some disadvantages:

- high metal consumption;
- low efficiency;
- poor balancing;
- low gearbox (reducer) service life;
- destruction of elements of the transforming mechanism;
- inconvenience of rearranging the connecting rod pin;
- high labor intensity of moving counterweights during of balancing process;
- the presence of significant unbalanced masses;
- the need to build a massive foundation.

Formulation of the problem

The listed disadvantages of beam-pumping units form the prerequisites for creating fundamentally new designs of sucker rod pump drives. At the same time, one of the main trends in this area is the development of beamless pumping units. The advantage of these rocker machines is characterised by small dimensions and metal consumption, lower power consumption and better dynamic characteristics (Mishchenko, 2003). The listed facts necessitate the search for new improved designs of sucker-rod pumps, one of which is the beamless pumping unit for sucker-rod pumps developed at the Department Machine Design of the Azerbaijan Technical University (Eurasian patent No. 032268 – Abdullaev et al., 2019).

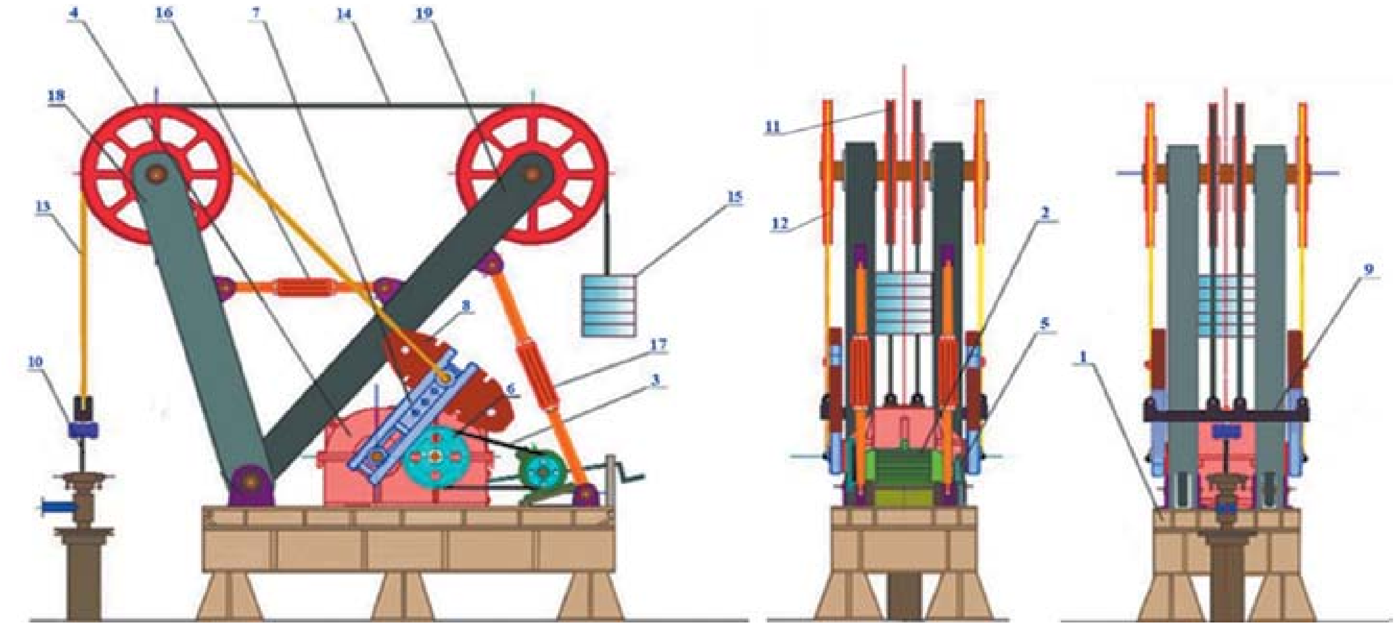


Fig. 1. Scheme of purposed new constructive solution of beamless pumping unit (for a description of the individual elements of the construction – see page 573)

Rys. 1. Schemat proponowanego nowego rozwiązania konstrukcyjnego zespołu pompy bez żurawia (opis poszczególnych elementów konstrukcji znajduje sie w tekście – str. 573)

The proposed design of the mechanical drive of sucker rod pumps for the operating of oil wells provides the following advantages over other types of oil production equipment:

- its energy consumption is about 1.5–1.7 times less than conventional beam-pumping unit;
- it extends the gearbox service life, due to the absence of negative torques on the output shaft;
- less sensitive to uneven foundation settlement;
- there is no massive swinging walking beam and horse head at the beam-pumping unit;
- increases the service life of the rod's column, since there are practically no dynamic load vibrations due to work in a symmetrical cycle;
- small dimensions;
- ability to free up space around the wellhead during installation and repair, and precise control of the trajectory of the rod suspension point along the vertical line;
- ability to fully unfold the front and rear racks during transportation of equipment to the installation site.

Figure 1 shows a scheme of a new solution of the beamless sucker-rod pump. The new solution of the beamless sucker-rod pump contains two cranks (7), rigidly fixed on both sides at the output ends of the driven shaft of the multi-stage reducer (4), which has only two shafts and a gear ratio of 1:125.

At one end of the drive shaft of the reducer, a stepped driven pulley (6) of the V-belt drive (3) is installed, and at the other output end, a two-disk brake (5) is located.

The mechanical drive comprises a frame (1) made of profile rolling in the form of two longitudinal cross-connects, two brackets for connecting the front pillars (18), two brackets for connecting the rear pillars (19), and two brackets for connecting the front rods (16) and two brackets for connecting rear rods (17). On the frame together with the reducer is installed a three-phase asynchronous electric motor (2).

As part of the transforming mechanism of the mechanical drive, there are also ropes (13) and (14) and blocks (11) and (12). At one end of the parallel ropes, a cross-piece (9) is suspended from which the rod's column (10) is fixed and at the other end – cranks with a counterweight (8) are fixed. On the other hand, with the parallel ropes (14), the traverse is connected to a movable counterweight (15) giving a gain in strength.

The lower end of the rod's column (10), rigidly connected to the traverse, is connected to the pump piston. The front and rear drive racks, pivotally connected to the frame brackets, are interconnected by front traction bars with right and left screw thread. In addition, the rear pillars with the help of the rear traction rods are also pivotally connected to the frame brackets.

Front and rear traction rods provide a change in the angles of inclination of the front and rear racks. These racks can be made telescopic to adjust the height of the stand depending on the stroke of the rod suspension. The lower ends (base) of the front and rear pillars are attached to the bracket on the hinged support with the possibility of deflecting to the right or left with the front rods to free space around the wellhead during repair and to precisely control the trajectory of the rod's suspension point along the vertical line. In addition, the connection of the pillars to the bracket on the hinged support makes it possible to completely unfold the front and rear racks of mechanical drive when it is being transported to the installation site. To reduce the load on the elements of the transforming mechanism by means of a flexible link to the traverse, a movable counterweight is additionally secured.

Solution of the problem

One of the adverse factors in the pumping unit is uneven efforts at the horse head during the movement of the polished rod from its lowest to its highest position. To reduce the uneven load on the electric motor of the pumping unit as well as to reduce power consumption, an additional balancing system (movable counterweight) is proposed, which allows loading the wellhead rod with a vertical force constantly directed upward (Abdullaev et al., 2019).

The proposed improved design of the sucker-rod pumping unit with an additional balancing system (movable counterweight) makes it possible to increase the operating efficiency of well pumps, increases the reliability of flexible traction and meets the requirements of technical safety during repair work. Using of this system allows to reduce the load on the cranks of the pumping unit by an average of 50%.

To simulate the operation of the proposed beamless pumping unit, a working model was manufactured and tested. The model simulates the operation of a real oil pumping unit. This small--scale model of the pumping unit is intended for widespread use in various conditions. The model is made of plastic and metal on a scale of 1:10, 700 mm long and 850 mm high. Figure 2 shows a model of the proposed beamless pumping unit.

Assessment of the loading of the beamless pumping unit

For oil producing enterprises, the tasks of ensuring reliable and efficient operation of oil pumping units, reducing the cost of its operation, maintenance and repair remain urgent. It should be noted that one of the key factors that have a significant impact on the MTBF of a pumping unit is its balancing quality, which determines the level of dynamic loads on the units of equipment and the value of specific energy consumption for lifting of fluid (Urazakov et al., 2019).

The essence of balancing the pumping units is to ensuring uniform loading of the gearbox and the drive motor during the up stroke and down stroke. This need is due to the fact that during the up stroke, the gearbox and the engine are loaded with a positive moment for lifting the rod columns and the liquid column. When the horse head moves down, the rod string ‘pulls’ the balancer down, hence the gearbox and the engine are loaded with a negative torque. This operating mode of the engine and gearbox is abnormal and leads to a sharp decrease in the performance of the gearbox and the engine (Zhuravlev, 2018). The changing of torque on the crank shaft (output shaft) of the gearbox, and, consequently, on the motor shaft at a balanced and unbalanced pumping units is shown in Figure 3.

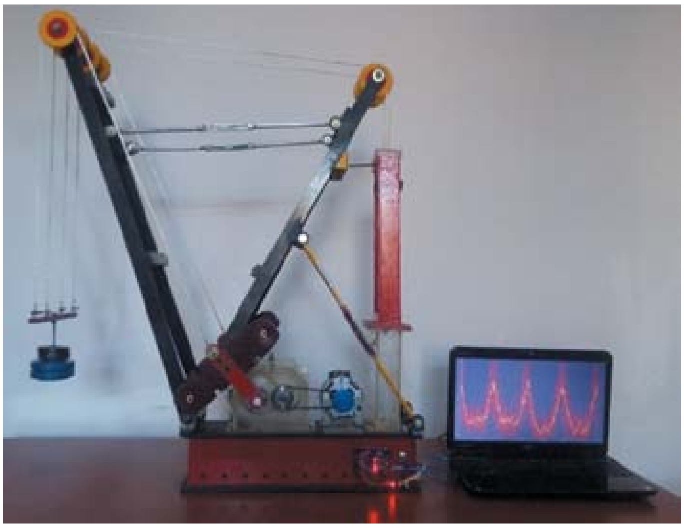


Fig. 2. Working model of the proposed beamless pumping unit

Rys. 2. Model roboczy proponowanego zespołu pompy bez żurawia

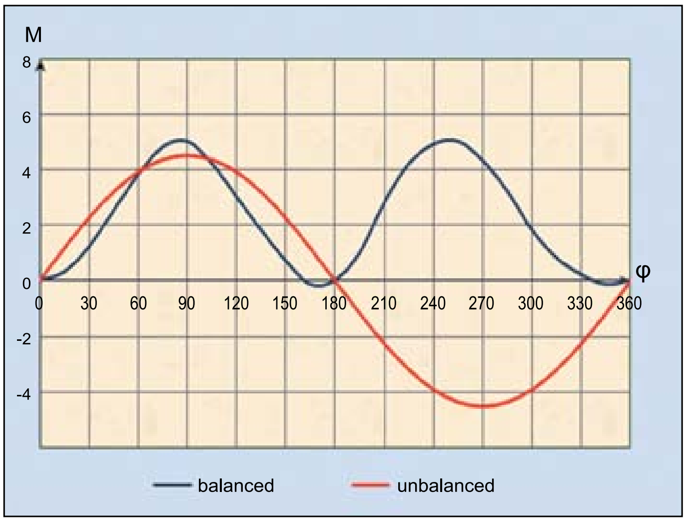


Fig. 3. Changing the torque on the output shaft of the pumping unit reducer

Rys. 3. Zmiana momentu obrotowego na wale wyjściowym reduktora zespołu pompowego

As can be seen from the graph, the change in the torque on the crank shaft of the gearbox at an unbalanced pumping unit occurs along a sinusoid. That is, when the rod’s suspension point moves up, the torque has a positive value, and when it moves down, it has negative values. This change of torque on the crank shaft of the gearbox creates an abnormal operation of both the engine and the gearbox and increases the wear of all units of the sucker-rod pumping unit.

At a balanced pumping unit, the torque value for both the up stroke and the down stroke is positive. This loading mode significantly increases the service life of the engine and gearbox of the mechanical drive of the sucker-rod pumping unit.

It can be seen from the graph that even in a properly balanced pumping unit, the values of negative loads arising at the moments of changing the direction of travel are not excluded. They are due to dynamic loads.

One of the ways to reduce the energy consumption of pumping units is to reduce the load on the cranks of the transforming mechanism. To reduce energy consumption during the operation of a sucker rod pump, a balancing system has been developed consisting of movable counterweights applied through a flexible traction directly to the wellhead rod, which allows to compensate for a part of the constant load at the rod suspension point due to the weight of the rod’s column in the liquid.

At present, in the oil fields of most countries, the assessment of loading and balancing of pumping units is carried out, as a rule, with the maximum instantaneous values of active power during the up stroke of rod suspension and the instantaneous values of the rotor rpm of the drive motor in one swing period by using current clamps that control the value of the acting current in the stator windings of an asynchronous electric motor (Goldstein et al., 2004; Ushakov and Demyanenko, 2008; Ziming et al., 2013; Gabor, 2015; Timofeev and Yasoveev, 2017; Ahmedov et al., 2019; Zyuzev and Bubnov, 2019).

According to the method based on the maximum instantaneous values of active power during the up stroke, the unbalance ratio is determined by the maximum instantaneous values of active power during the up stroke $P_{up.\max}$ and down stroke $P_{dw.\max}$ of the rod.

$$K = \frac{P_{up.\max} - P_{dw.\max}}{P_{up.\max} + P_{dw.\max}} \cdot 100\% \tag{1}$$

The method based on the instantaneous values of the rotor rpm of the drive engine for one swing period consists in determining the minimum values of the instantaneous speed during the up stroke $V_{1\min}$ and down stroke $V_{2\min}$ of the rod, comparing these values and determining the state of equilibrium in the given condition (Zyuzev and Bubnov, 2019):

$$\left| V_{1\min} - V_{2\min} \right| < \frac{0{,}1(V_{1\min} + V_{2\min})}{2} \tag{2}$$

A common disadvantage of the methods for the maximum instantaneous values of active power during the up stroke of the rod and instantaneous values of the rotor rpm of the drive engine for one swing period is that the instantaneous values of speed or power are used to determine the equilibrium, not the dynamic changes in values during the swing period of the sucker rod pump.

There is a known method (Goldstein et al., 2004) where instantaneous values of current and voltage at the input of the electric drive are used as the initial data, on the basis of which the consumed reactive power is calculated and carried out it is harmonic analysis, then finding the ratio of the second harmonic to that of the first; the value of the obtained ratio is then compared with the reference for this well.

$$J_k = \sqrt{\sum_{k=0}^{L-1} \frac{i_k^2(t)}{L}} \tag{3}$$

$$U_k = \sqrt{\sum_{k=0}^{L-1} \frac{u_k^2(t)}{L}} \tag{4}$$

where:

$i(t)$ and $u(t)$ – instantaneous current and voltage values obtained from current and voltage sensors, respectively, and digitised,

J and U – operating current and voltage values defined for period of power line frequency,

k – ranges from 0 to L-1,

L – is the number of discrete values at the period of power line frequency 50 Hz, L depends on the time sampling interval.

In the manuals for the operation of oil wells, instructions are traditionally given on determining the balance factor by using a clamp meter (Ziming et al., 2013; Timofeev and Yasoveev, 2017). According to the manual, it is necessary to determine the maximum values of the current during the stroke of the rod of the rod installation up IB and down IH, and then to find the unbalance ratio of the pumping unit.

$$K = \frac{J_{up} - J_{dw}}{J_{up} + J_{dw}} \cdot 100\% \tag{5}$$

The sucker-rod pumping unit is considered balanced if the unbalance ratio does not exceed 5%.

The microcontroller Arduino UNO was used to measure the amount of current in the stator windings of the asynchronous electric motor in the proposed model of beamless pumping unit. To measure current with the Arduino UNO, we used the ACS712 sensor from Allegro Microsystems (measurement error no more than ±1%, at temperatures from 25 to 150°C). Pairing the ACS712 current sensor with the Arduino UNO helps to accurately measure the motor current. This sensor is based on the Hall effect, and the measuring system has a built-in Hall effect device. The schematic diagram of connecting the ACS712 current sensor to the Arduino is shown in Figure 4.

Assessment of the load on the pumping unit by using of movable counterweights

To determine the effectiveness of using movable counterweights by using of the Arduino UNO microcontroller, the ACS712 current sensor and a Kalman filter on a working model of a beamless pumping unit, experiments were carried out, the results of which are shown in Table 1, and are graphically represented in Figure 5.

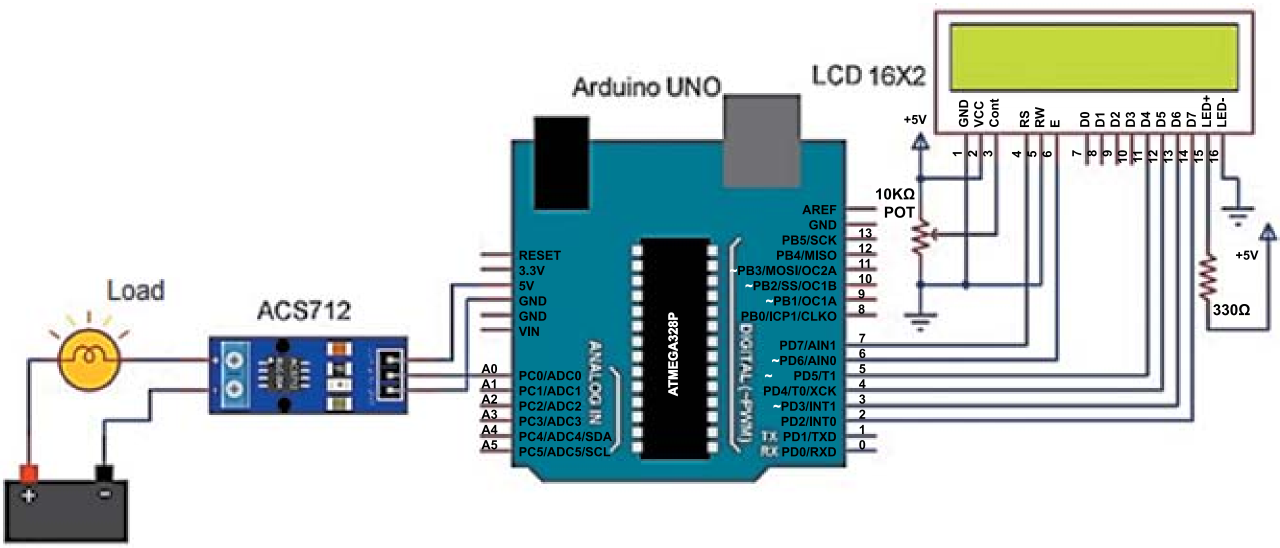


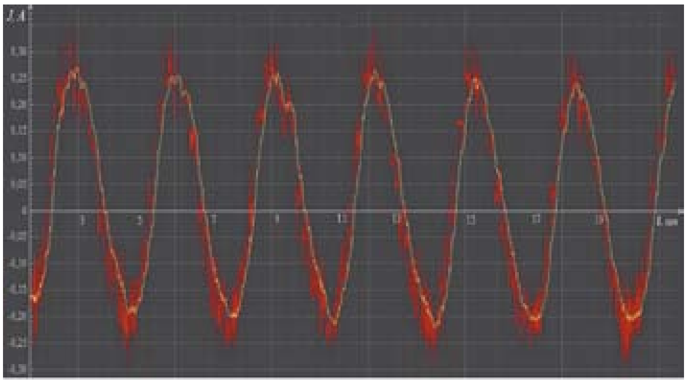
Fig. 4. Schematic diagram of connecting ACS712 current sensor to Arduino UNO

Rys. 4. Schemat podłączenia czujnika prądu ACS712 do Arduino UNO

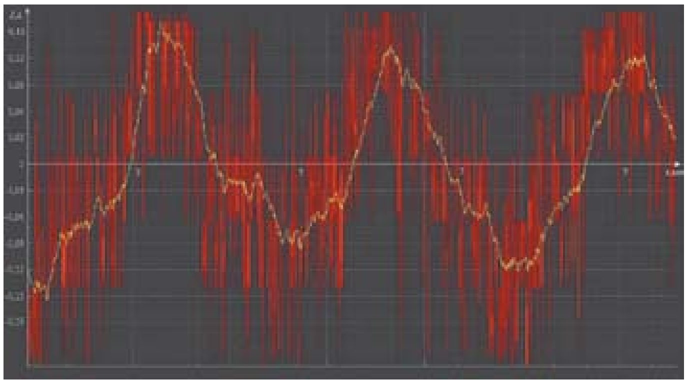
Table 1. The result of the experiment of the balancing of the pumping unit using only movable counterweights

Tabela 1. Wynik eksperymentu wyważania zespołu pompującego przy użyciu wyłącznie przesuwnych przeciwwag

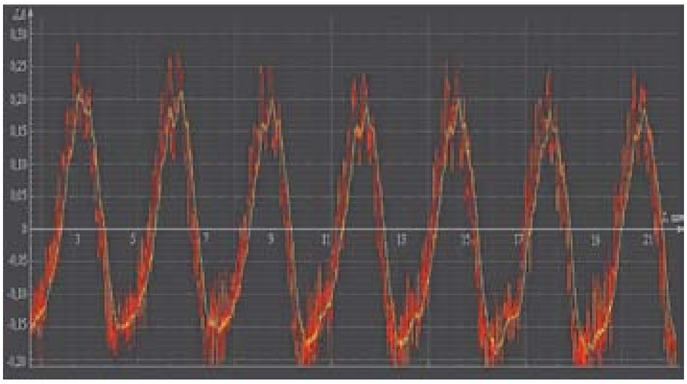
Stage of experiment	Load acting on the rod suspension point, G_{rod} [kg]	Weight of movable counterweights, G_{cw} [kg]	Weight of rotary counterweights, G_r [kg]	Maximum current, J [A] when rod suspension point moves up	Maximum current, J [A] when rod suspension point moves down
I (Fig. 5a)	3	0	0	+0.27	–0.200
II (Fig. 5b)	3	0.75	0	+0.21	–0.180
III (Fig. 5c)	3	1.50	0	+0.16	–0.160
IV (Fig. 5d)	3	2.25	0	+0.13	–0.120



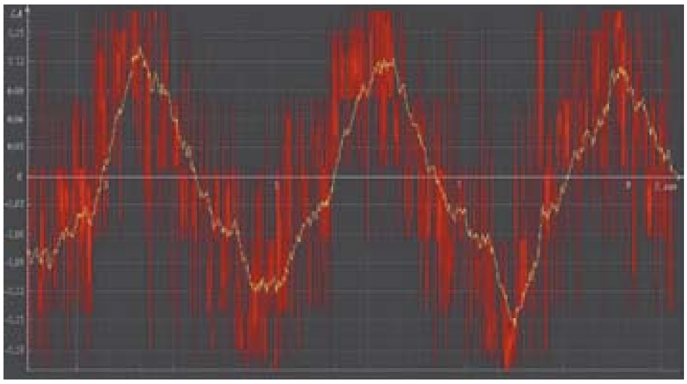
a) $G_{rod} = 3$ kg; $G_w = 0$; $G_r = 0$



c) $G_{rod} = 3$ kg; $G_w = 1.5$ kg; $G_r = 0$



b) $G_{rod} = 3$ kg; $G_w = 0.75$ kg; $G_r = 0$



d) $G_{rod} = 3$ kg; $G_w = 2.25$ kg; $G_r = 0$

Fig. 5. Graphs of changes in the current consumed by the motor under different loading conditions of the pumping unit by balancing with movable counterweights

Rys. 5. Wykresy zmian prądu pobieranego przez silnik w różnych warunkach obciążenia zespołu pompowego spowodowanych wyważeniem przesuwnymi przeciwwagami

As can be seen from the analysis of the graphs, the value of the current consumed by the motor sharply decreases with the increasing weight of movable counter-weights. Therefore, the use of movable counterweights in the beamless pumping unit makes it possible for the electric motor to consume approximately 2 times less current.

Combined balancing of the beamless pumping unit

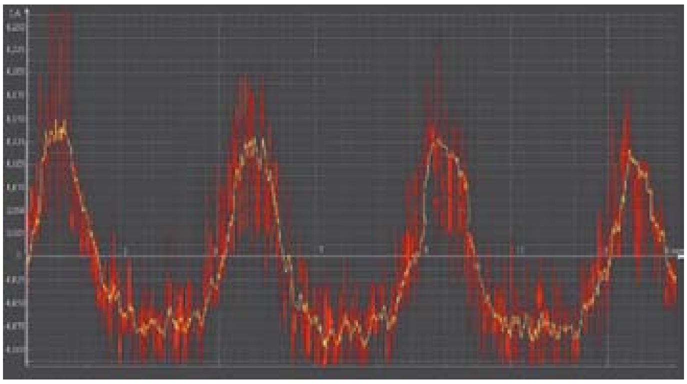
As already mentioned, to equalise the load on the electrical engine and reducer during one working cycle, as well as to reduce the power of the electrical engine in it is mechanical drive, the pumping units are equipped with a balancing device. The function of this device is to collect potential energy when the rod's column moves down and return it when it moves up. On the studied beamless pumping unit, a combined balancing method was used, that is, balancing was performed with both movable and rotary counterweights.

To assessment the effectiveness of using the balancing device, the experiments were carried out on a working model of a beamless pumping unit, the results of which are shown in Table 2, and are graphically represented in Figure 6.

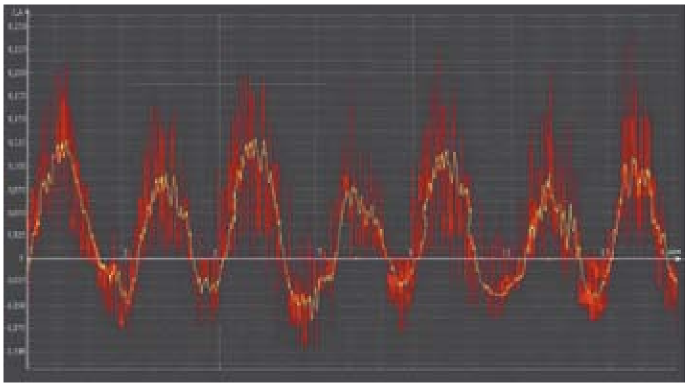
Table 2. The result of the experiment of the balancing of the pumping unit using movable and rotary counterweights (combined balancing)

Tabela 2. Wynik eksperymentu wyważania zespołu pompującego przy użyciu przesuwnych i obrotowych przeciwwag (wyważanie łączone)

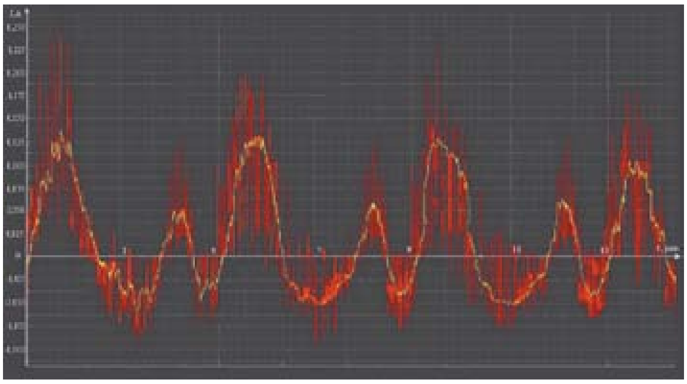
Stage of experiment	Load acting on the rod suspension point, G_{rod}	Weight of movable counterweights, G_{cw}	Weight of rotary counterweights, G_r	Maximum current, J [A]	
	[kg]	[kg]	[kg]	when rod suspension point moves up	when rod suspension point moves down
I (Fig. 6a)	3	2.25	0.25	+0.125	–0.100
II (Fig. 6b)	3	2.25	0.5	+0.128	+0.056 –0.050
III (Fig. 6c)	3	2.25	0.75	+0.135	+0.088 –0.035
IV (Fig. 6d)	3	2.25	1.0	+0.150	+0.150 –0.020



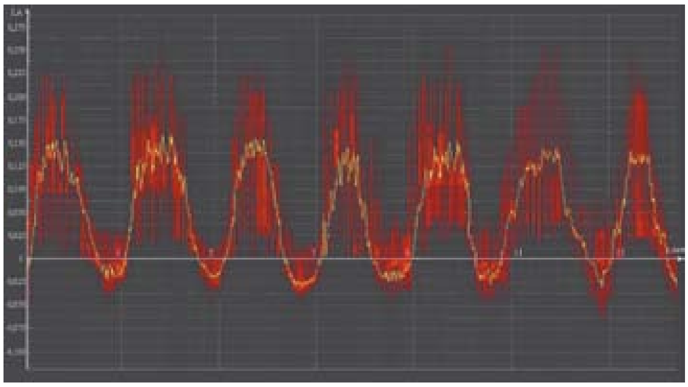
a) G_{rod} = 3 kg; G_w = 2.25 kg; G_r = 0.25 kg



c) G_{rod} = 3 kg; G_w = 2.25 kg; G_r = 0.75 kg



b) G_{rod} = 3 kg; G_w = 2.25 kg; G_r = 0.5 kg



d) G_{rod} = 3 kg; G_w = 2.25 kg; G_r = 1.0 kg

Fig. 6. Graphs of the change in the current consumed by the motor under different loading conditions of the pumping unit with combined balancing

Rys. 6. Wykresy zmian prądu pobieranego przez silnik w różnych warunkach obciążenia zespołu pompowego z łączonym wyważeniem

During experiments, the weight of the movable counterweights was taken as a constant, and the weight of the rotary counterweights gradually increased.

As can be seen from the analysis of the obtained current signals, at the first stage of the experiment, the pumping unit is in a nonequilibrium state, and the electric motor and the reducer of the mechanical drive are loaded with an approximately cyclically varying load (Fig. 6a). At the second stage of the experiment, the device is loaded with a relatively small negative load, but the pumping unit as a whole is still not in equilibrium (Fig. 6b). At the third stage of the experiment, although the pumping unit is partially in equilibrium, it is still not in complete equilibrium (Fig. 6c). And at the fourth stage of the experiment, the pumping unit is almost completely balanced, and the electric motor and the reducer are loaded with an equal load when the rod suspension point moves up and down (Fig. 6d). As can be seen, even in this case, the current consumed by the electric motor is slightly negative when the rod's suspension point the moves from top dead center to bottom dead center or vice versa. This is due to the inertial forces generated by the moving masses of the pumping unit. It is not possible to completely eliminate this situation on the sucker-rod pumping unit. However, an attempt should be made to minimise the amount of negative current in a properly balanced pumping unit.

Results

Regular recording of the current signals consumed by the electric motors of the mechanical drive of the beamless pumping unit allows obtaining relevant and reliable information about the operational parameters of the sucker rod pump, and based on the data obtained, it is most effective and reliable to control the loading of the sucker-rod pumping units and to efficiently balance the sucker rod pumping unit. Due to this, energy consumption for lifting formation fluid and dynamic loads on the parts of beamless pumping unit are reduced.

The study of information on the magnitude and nature of the change in the loading of the electric motor of the pumping unit makes it possible to assess the technical condition of the elements of the deep-well pumping unit.

The research results presented in this article prove the promising development of the means for monitoring the technical condition of equipment and for assessing the magnitude and nature of changes in the current consumed by the electric motor of the transforming mechanism of the pumping unit.

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