Building the Dynamometer Card of Sucker Rod Pump Using Power Consumption of the Eclectic Motor of Pumping Unit

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***Abstract*— The present paper gives analytical expression of relation between gravity force on the polished rod and power consumption of the electric motor from the power line with allowance for parameters of the pumping unit, allowing one to build a dynamometer card of sucker rod pump based on the obtained wattmeter card.**

***Keywords*— dynamometer card; electric motor power consumption; oil extraction; rod force; sucker rod pump; wattmeter card**

I. INTRODUCTION

The most common and studied method of diagnostics of the condition of sucker rod pumping units (SRPU) is dynamometry [1], the process of reading the relation between force P(S) on the polished rod of the pumping unit (PU) and displacement S of the rod hanger point. Being a form of the obtained curves, the dynamometer card shows changes of load P(S) in the rod hanger point depending on their displacement S during sucker rod pumping. Nature of deviation of the dynamometer card from the norm allows one to determine various faults in SRPU operation. However, this method is known to lack sufficient accuracy and reliability due to imperfection of devices showing the unit operation in the form of dynamometer card. Besides, the method completely rules out diagnostics of ground equipment and allows only diagnosing its underground components.

A more reliable diagnostic method for SRPU can be wattmetry, that is the process of obtaining wattmeter card (WMC), showing the relation between power $N(\varphi)$ consumed by the PU electric motor and the crank angle φ [2-5]. In this case, there is no need to use converters of mechanic units into electric signals, alternating current power sensor being used. It should however be noted that dynamometer cards are mainly used today for diagnostics of faults of sucker rod pumps, since their deciphering is better studied than that of wattmeter cards. Study of fault symptoms from wattmeter cards is a long process that requires numerous experiments.

If we assume that the analytical expression of $P(N)$ relation throughout the whole pumping cycle is known, then measured values of power (*N*) can be used to calculate the value of load (*P*). *P*(*S*) relation, deciphering of errors in which is well studied, can be built using calculated load values. In that case, the problem of determining the functional relation between power consumption of the electric motor and force on the rod per pumping cycle in time becomes topical.

Topicality of the problem is due to two circumstances:

- operating personnel at oil and gas extracting facilities is accustomed to a priori diagnostics using dynamometer cards, while WMC diagnostics is almost never applied;
- intelligent diagnostics by application of new robust noise monitoring technologies [6] using WMC requires creating reference patterns reflecting different conditions of equipment. Created dynamometer card patterns will be useful in that matter.

II. PROBLEM STATEMENT

It is known [7] that sensitivity, accuracy and reliability of sensors measuring values of force on the rod string hanger are much lower compared with those measuring power consumption of the electric motor. Besides, assembly, installation and further operation of force sensors require extra care. Repair of sensors leads to forced stopping of the pumping unit. By obtaining analytical expression of the relation between power consumption of the electric motor from power line and the force on the rod string hanger throughout the whole pumping cycle, one can avoid the mentioned shortcomings. Thus, the problem is to determine the functional relation between power consumption of the electric motor and the force on the rod.

III. PROBLEM SOLUTION

Power $N(\varphi)$ consumed by the electric motor is conditioned basically by the following two forces: $P_1(\varphi)$, balancing load weight, and $P_2(\varphi)$, force on the rod. Our aim is to establish the functional relation between power $N(\varphi)$ consumed by the electric motor and force $P_2(\varphi)$ on the rod.

Let us introduce a coordinate system and place its origin at the concurrence of the horizontal line crossing the center of the lead block and the vertical line crossing the axis of rotation of the pump walking beam (Fig. 1).

Assume that in arbitrary moment t ($t \geq 0$), angle $\angle ECO = \alpha(t)$ and $\angle\left(\overrightarrow{CO}, \overrightarrow{BF}\right) = \varphi(t)$. For the sake of simplicity, let us not name argument t explicitly and let us write α and φ instead of $\alpha(t)$ and $\varphi(t)$ respectively. Assuming

$$CE = R, EA = L, OB = H, AB = \lambda_1, BF = \lambda_2$$

let us determine the coordinates of points (Fig. 2):

$$E(R\cos\alpha - \lambda_1, R\sin\alpha), B(0, H),$$

$$A(-\lambda_1\cos\varphi, H + \lambda_1\sin\varphi).$$

Let us consider that the crank mechanism rotates at a constant angular velocity ω, i.e. $\alpha(t) = \omega \cdot t$. The following is the analysis of the above-mentioned forces.

Balancing load weight can be regarded as constantly ($P_1(t) \equiv P_1$) applied to point E, and all joints being swivels, it does not create a turning moment. Vertical component of speed of point E being $v_1(t) = \omega \cdot R \cdot \cos(\omega t)$, the power required for its motion will be $N_1(t) = P_1 \cdot v_1(t)$ or

$$N_1(t) = P_1 \cdot \omega \cdot R \cdot \cos(\omega t), \qquad (1)$$

Let us determine the maximum angle φ_0, at which the rod is in its lowest position with $t = 0$ (Fig.2)

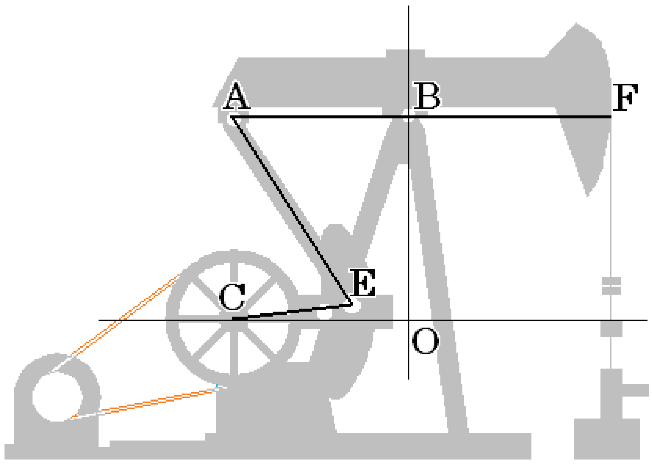

Figure 1.

$$(\lambda_1 - \lambda_1\cos\varphi_0)^2 + (H + \lambda_1\sin\varphi_0)^2 = (L+R)^2.$$

Hence

$$\lambda_1^2 - 2\lambda_1^2\cos\varphi_0 + \lambda_1^2\cos^2\varphi_0 +$$

$$+ H^2 + 2H\lambda_1\sin\varphi_0 + \lambda_1^2\sin^2\varphi_0 = (L+R)^2,$$

$$2\lambda_1(H\sin\varphi_0 - \lambda_1\cos\varphi_0) = (L+R)^2 - H^2 - 2\lambda_1^2,$$

$$\varphi_0 = \arcsin\frac{(L+R)^2 - H^2 - 2\lambda_1^2}{2\lambda_1} + \operatorname{arctg}\frac{\lambda_1}{H}.$$

Let us calculate the value $\alpha(t) = \alpha_0$ at $\varphi(t) = \varphi_0$. Since $\cos\alpha_0 = \dfrac{\lambda_1\sin\varphi_0 + H}{L+R}$, we obtain

$$\alpha_0 = \arccos\frac{\lambda_1\sin\varphi_0 + H}{L+R}.$$

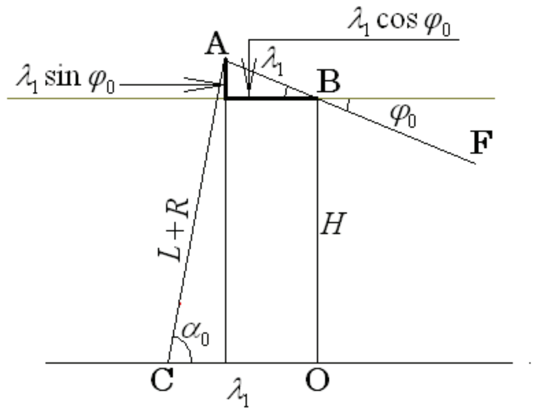

Figure 2.

To calculate power $N_2(t) = P_2(t) \cdot v_2(t)$, let us establish the relation between speed velocity of the rod and crank motion. Let us establish the relation between $\alpha = \alpha(t)$ and the inclination angle of the beam $\varphi = \varphi(t)$ (Fig. 3). For this purpose, let us first calculate the squared length of segment EA, following the coordinates of A and E : $(R\cos\alpha - \lambda_1 + \lambda_1\cos\varphi)^2 + (R\sin\alpha - H - \lambda_1\sin\varphi)^2$. Making this expression equal to L^2, we find

$$\lambda_1^2 + R^2\cos^2\alpha - 2R\lambda_1\cos\alpha + \lambda_1^2\cos^2\varphi - 2\lambda_1^2\cos\varphi +$$
$$+ 2R\lambda_1\cos\alpha\cos\varphi + H^2 + \lambda_1^2\sin^2\varphi + R^2\sin^2\alpha +$$
$$+ 2H\lambda_1\sin\varphi - 2HR\sin\alpha - 2R\lambda_1\sin\alpha\sin\varphi = L^2$$

or

$$\lambda_1^2\cos\varphi - R\lambda_1\cos\alpha\cos\varphi - H\lambda_1\sin\varphi + R\lambda_1\sin\alpha\sin\varphi =$$
$$= G^2 - R\lambda_1\cos\alpha - HR\sin\alpha. \qquad (2)$$

where

$$G^2 = \frac{1}{2}\left(R^2 + H^2 - L^2\right) + \lambda_1^2.$$

Let us denote $a = \lambda_1(\lambda_1 - R\cos\alpha)$, $b = \lambda_1(R\sin\alpha - H)$, $f = G^2 - R\lambda_1\cos\alpha - HR\sin\alpha$, $c = \sqrt{a^2 + b^2}$. Then from (2), we obtain

$$\varphi = \arccos\frac{f}{c} + \mathrm{arctg}\frac{b}{a}$$

Obviously, linear speed of the beam is

$$v_2(t) = \lambda_2 \frac{d\varphi(t)}{dt}.$$

We can determine this speed by calculating $\frac{d\varphi(t)}{dt}$ from the following formula:

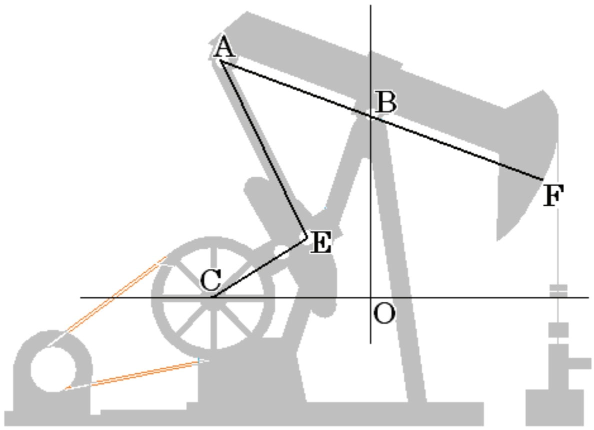

Figure 3.

$$\frac{d\varphi(t)}{dt} = \frac{R}{\lambda_1} \cdot \frac{(\lambda_1 \sin\alpha - H\cos\alpha) - \lambda_1 \sin(\alpha+\varphi)}{R\sin(\alpha+\varphi) - (\lambda_1 \sin\varphi + H\cos\varphi)} \cdot \frac{d\alpha(t)}{dt}.$$

Considering the above-mentioned, we will obtain

$$v_2(t) = \frac{\lambda_2 R\omega}{\lambda_1} \cdot \frac{(\lambda_1 \sin\alpha - H\cos\alpha) - \lambda_1 \sin(\alpha+\varphi)}{R\sin(\alpha+\varphi) - (\lambda_1 \sin\varphi + H\cos\varphi)}.$$

Now, considering that

$$N(t) = N_1(t) + N_2(t)$$

and presentation

$$N_2(t) = P_2(t) \cdot v_2(t),$$

we can write the following formula describing the relation between $N(t)$ and $P_2(t)$:

$$N(t) = P_1 \cdot \omega \cdot R \cdot \cos(\omega t) +$$

$$+ P_2(t) \cdot \frac{\lambda_2 R\omega}{\lambda_1} \cdot \frac{(\lambda_1 \sin\alpha - H\cos\alpha) - \lambda_1 \sin(\alpha+\varphi)}{R\sin(\alpha+\varphi) - (\lambda_1 \sin\varphi + H\cos\varphi)}.$$

Hence, we obtain the following for $P_2(t)$:

$$P_2(t) = \frac{\lambda_1}{\lambda_2 R\omega} \frac{R\sin(\alpha+\varphi) - (\lambda_1 \sin\varphi + H\cos\varphi)}{(\lambda_1 \sin\alpha - H\cos\alpha) - \lambda_1 \sin(\alpha+\varphi)} \times$$
$$\times \left(N(t) - P_1 \cdot \omega \cdot R \cdot \cos(\omega t)\right)$$

IV. Conclusion

Thus, analytical expression has been obtained showing the relation between the power consumed by the electric motor from power line and the force on the polished rod during pumping unit operation. This expression allows to use calculated instantaneous power $N(\varphi)$ to determine instantaneous force $P_2(\varphi)$ for the whole operation period of the pumping unit, which makes it possible to build a dynamometer card easily read by operating personnel of an oil field.

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