RESEARCH CONCERNING THE SIMULATION OF THE OPERATION OF CONVENTIONAL SUCKER ROD PUMPING UNITS

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DOI: 10.51865/JPGT.2021.02.04

ABSTRACT

In the paper is presented a method for obtaining the variation during a cinematic cycle of the motor torque at the crankshaft in the case of the conventional sucker rod pumping units. The calculation method has been transposed into a computer program which allows establishing the influence of different constructive and operating parameters of the pumping units on the variation of the motor torque at the crankshaft. Finally, a series of results of the simulations performed in the case of a C-640D-305-120 pumping unit are presented.

Keywords*:* pumping units, motor torque, balancing, inertia forces and moments

INTRODUCTION

It is well known that conventional sucker rod pumping units are used intensively in oil extraction, so the study of their optimal operation represents a topical issue [1-10]. On the other hand, the study of the kinematics and dynamics of the mechanism of these pumping units is part of a broader issue specific to the theory of mechanisms and machines [11-19]. This paper presents a method for obtaining the variation during a cinematic cycle of the motor torque at the crankshaft in the case of the conventional sucker rod pumping units. A computer program which allows establishing the influence of different constructive and operating parameters of the pumping units on the variation of the motor torque at the crankshaft has been developed. Some simulations results obtained in the case of a C-640D-305-120 pumping unit are finally presented.

THEORETICAL CONSIDERATIONS AND SIMULATION RESULTS

In Figure 1 is represented the mechanism of a conventional sucker rod pumping unit. The positional and cinematic analysis of this mechanism may be accomplished with the method of projecting the closed and independent vector contours [20].

By projecting the vector equation: $\overline{OA}+\overline{AB}+\overline{BC}+\overline{CO}=0$ (Figure 1) on (Ox) and (Oy) axes the following system of equations is obtained:

$$\begin{cases} l_1 \cdot \cos\varphi_1 + l_2 \cdot \cos\varphi_2 + l_3 \cdot \cos\varphi_3 - x_C = 0 \\ l_1 \cdot \sin\varphi_1 + l_2 \cdot \sin\varphi_2 + l_3 \cdot \sin\varphi_3 - y_C = 0 \end{cases} \tag{1}$$

where: $l_1 = OA$, $l_2 = AB$ and $l_3 = BC$.

By solving the system of equations (1), the angles φ_2 and φ_3 may be calculated from the following relations:

$$A_2 \cdot \cos\varphi_2 + B_2 \cdot \sin\varphi_2 = C_2 \tag{2}$$

where:

$$\begin{cases} A_2 = 2 \cdot l_1 \cdot l_2 \cdot \cos\varphi_1 - 2 \cdot l_2 \cdot x_C \\ B_2 = 2 \cdot l_1 \cdot l_2 \cdot \sin\varphi_1 - 2 \cdot l_2 \cdot y_C \\ C_2 = l_3^2 - l_1^2 - l_2^2 - x_C^2 - y_C^2 + 2 \cdot l_1 \cdot x_C \cdot \cos\varphi_1 + 2 \cdot l_1 \cdot y_C \cdot \sin\varphi_1 \end{cases} \tag{3}$$

$$\varphi_3 = \mathrm{ATAN2}\left(-\frac{1}{l_3}(l_1 \cdot \sin\varphi_1 + l_2 \cdot \sin\varphi_2 - y_C), -\frac{1}{l_3}(l_1 \cdot \cos\varphi_1 + l_2 \cdot \cos\varphi_2 - x_C) \right) \tag{4}$$

where: $\mathrm{ATAN2}(y, x)$ calculates arctan(y/x) by taking into account the signs of x and y.

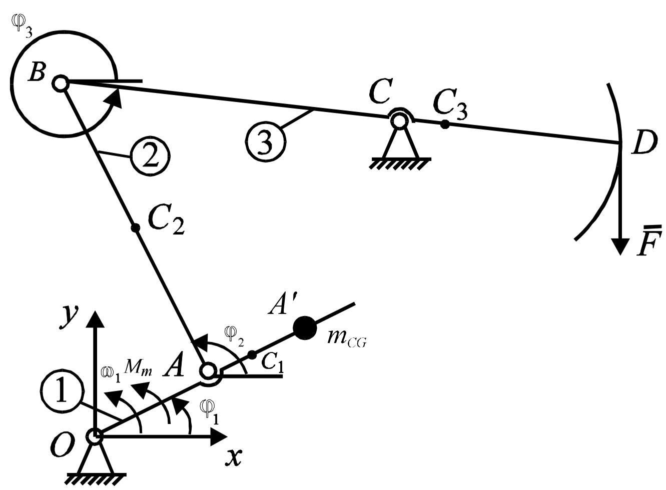

Figure 1. The mechanism of a conventional pumping unit

The angular speeds ω_j, $j = 2{,}3$, may be calculated as follows:

$$\omega_j = \dot{\varphi}_j = \frac{\mathrm{d}\varphi_j}{\mathrm{d}\varphi_1} \cdot \frac{\mathrm{d}\varphi_1}{\mathrm{d}t} = \omega_1 \cdot \frac{\mathrm{d}\varphi_j}{\mathrm{d}\varphi_1};\ j = 2{,}3 \tag{5}$$

where: ω_1 is the angular speed of the cranks. By considering that ω_1 is constant during the pumping unit operation, the angular accelerations ε_j, $j = 2{,}3$, may be calculated as follows:

$$\varepsilon_j = \dot{\omega}_j = \frac{\mathrm{d}^2\varphi_j}{\mathrm{d}\varphi_1^2} \cdot \omega_1^2;\ j = 2{,}3 \tag{6}$$

The coordinates of the mass centers $C_i, i=1,2,3$, corresponding to the cranks, connecting rods and to the rocker may be calculated with the relations:

$$\begin{cases} x_{C_1} = OC_1 \cdot \cos\varphi_1; \quad y_{C_1} = OC_1 \cdot \sin\varphi_1 \\ x_{C_2} = OA \cdot \cos\varphi_1 + AC_2 \cdot \cos\varphi_2; \quad y_{C_2} = OA \cdot \sin\varphi_1 + AC_2 \cdot \sin\varphi_2 \\ x_{C_3} = OA \cdot \cos\varphi_1 + AB \cdot \cos\varphi_2 + BC_3 \cdot \cos\varphi_3 \\ y_{C_3} = OA \cdot \sin\varphi_1 + AB \cdot \sin\varphi_2 + BC_3 \cdot \sin\varphi_3 \end{cases} \tag{7}$$

The projections on (Ox) and (Oy) axes of the speeds and of the accelerations of the mass centers $C_i, i=1,2,3$, by considering that ω_1 is constant during the pumping unit operation, may be calculated as follows:

$$\left(v_{C_i}\right)_x = \dot{x}_{C_i} = \frac{\mathrm{d}x_{C_i}}{\mathrm{d}\varphi_1} \cdot \frac{\mathrm{d}\varphi_1}{\mathrm{d}t} = \omega_1 \cdot \frac{\mathrm{d}x_{C_i}}{\mathrm{d}\varphi_1}; \; i=1,2,3 \tag{8}$$

$$\left(v_{C_i}\right)_y = \dot{y}_{C_i} = \frac{\mathrm{d}y_{C_i}}{\mathrm{d}\varphi_1} \cdot \frac{\mathrm{d}\varphi_1}{\mathrm{d}t} = \omega_1 \cdot \frac{\mathrm{d}y_{C_i}}{\mathrm{d}\varphi_1}; \; i=1,2,3 \tag{9}$$

$$\left(a_{C_i}\right)_x = \ddot{x}_{C_i} = \frac{\mathrm{d}^2 x_{C_i}}{\mathrm{d}\varphi_1^2} \cdot \omega_1^2; \; i=1,2,3 \tag{10}$$

$$\left(a_{C_i}\right)_y = \ddot{y}_{C_i} = \frac{\mathrm{d}^2 y_{C_i}}{\mathrm{d}\varphi_1^2} \cdot \omega_1^2; \; i=1,2,3 \tag{11}$$

The motor torque M_m at the crankshaft may be calculated by expressing the dynamic equilibrium in instantaneous powers corresponding to the weights of all the components of the pumping unit mechanism, to the inertia forces and moments and to the force $\overline{F}$ (Figure 1) acting at the polished rod:

$$\overline{M}_m \cdot \overline{\omega}_1 + \sum_{j=1}^{3} \overline{G}_j \cdot \overline{v}_{C_j} + \overline{G}_{CG} \cdot \overline{v}_{A'} + \sum_{j=1}^{3} \overline{F}_{ij} \cdot \overline{v}_{C_j} + \overline{F}_{iCG} \cdot \overline{v}_{A'} + \sum_{j=1}^{3} \overline{M}_{ij} \cdot \overline{\omega}_j + \overline{F} \cdot \overline{v}_D = 0 \tag{12}$$

where: $\overline{G}_j, \overline{F}_{ij}, \overline{M}_{ij}, j=1,2,3$, are the weights, the inertia forces and the inertia moments corresponding to the cranks, connecting rods and to the rocker, respectively; $\overline{G}_{CG}, \overline{F}_{iCG}$ are the weight and the inertia force corresponding to the counterweights whose total mass is m_{CG} (Figure 1); $\overline{v}_{A'}$ is the speed of the point where the mass of the counterweights is considered to be concentrated (Figure 1); $\overline{v}_D$ is the speed of the point where the force $\overline{F}$ at the polished rod acting (Figure 1).

A computer program that simulates the operation of the mechanism of the conventional sucker rod pumping units has been developed. Some simulations results obtained in the case of a C-640D-305-120 pumping unit are presented below. The dimensions of the component elements are in this case as follows: $OA = 0.762$ m; $AB = 3.391$ m; $BC = 2.822$ m; $CD = 3.937$ m; $OA' = 1.295$ m.

The coordinates of point C (Figure 1) are: $x_C = 2.189\ \mathrm{m}$; $y_C = 3.505\ \mathrm{m}$. The total mass of the counterweights is $m_{CG} = 4808\ \mathrm{kg}$ and the linear masses of the cranks, connecting rods and of the rocker are: $q_1 = 722\ \mathrm{kg/m}$; $q_2 = 34\ \mathrm{kg/m}$ and $q_3 = 300\ \mathrm{kg/m}$.

The crank angles φ_{1d} and φ_{1a} corresponding to the beginning of the upward and downward movements of the sucker rod column have the values 89° and 267°, respectively. The manner of obtaining the values of the angles φ_{1d} and φ_{1a} is presented in [8]. In Figure 2 is presented the variation of the force $\overline{F}$ at the polished rod during a cinematic cycle, beginning with the angle φ_{1d}, when the angular speed ω_1 is equal to $6\ \mathrm{rot/min}$.

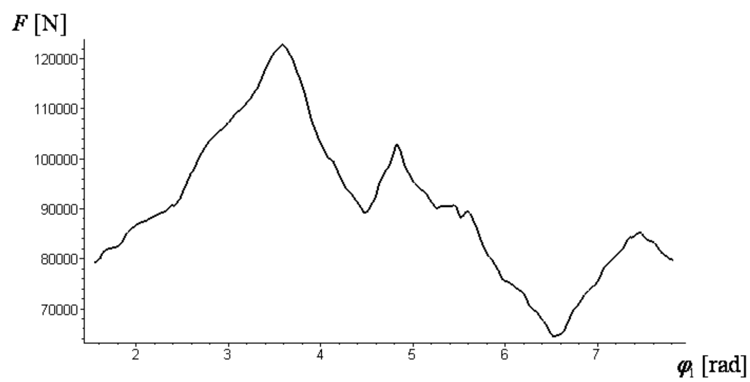

Figure 2. The variation of the force at the polished rod

In Figure 3 is represented the variation of the motor torque M_m at the crankshaft during a cinematic cycle, beginning with the angle φ_{1d}.

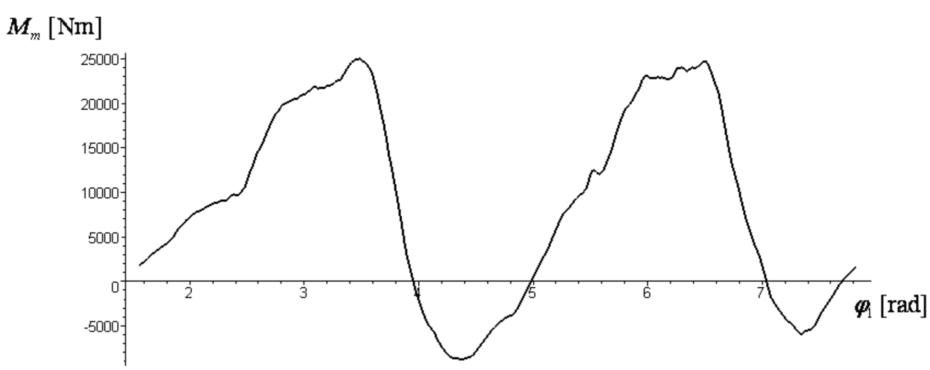

Figure 3. The variation of the motor torque at the crankshaft

In Figure 4 is represented the variation of the moment M_m^G due to the weights of the components: $M_m^G = -\frac{1}{\omega_1} \cdot \left(\sum_{j=1}^{3} \overline{G}_j \cdot \overline{v}_{C_j} + \overline{G}_{CG} \cdot \overline{v}_{A'} \right)$ and in Figure 5 is represented the variation of the moment M_m^F due to the force at the polished rod: $M_m^F = -\frac{1}{\omega_1} \cdot \left(\overline{F} \cdot \overline{v}_D \right)$.

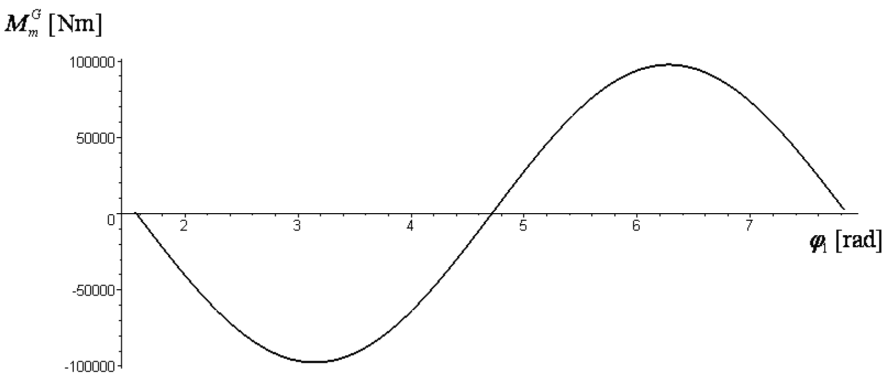

Figure 4. The variation of the moment M_m^G

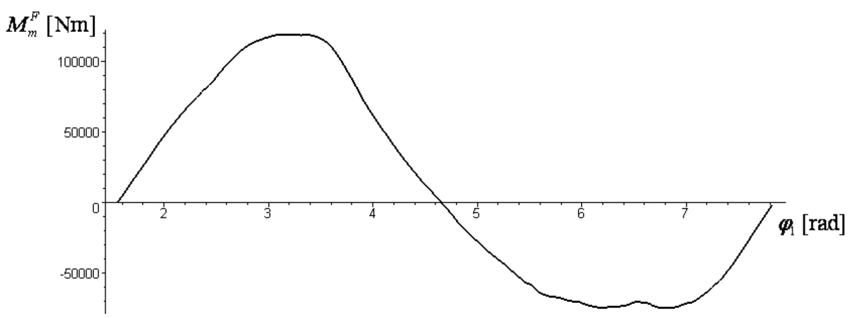

Figure 5. The variation of the moment M_m^F

In Figure 6 is represented the variation of the moment $M_m^{F_i}$ due to the inertia forces: $M_m^{F_i} = -\frac{1}{\omega_1} \cdot \left(\sum_{j=1}^{3} \overline{F}_{ij} \cdot \overline{v}_{C_j} + \overline{F}_{iCG} \cdot \overline{v}_{A'} \right)$ and in Figure 7 is represented the variation of the moment $M_m^{M_i}$ due to the inertia moments: $M_m^{M_i} = -\frac{1}{\omega_1} \cdot \left(\sum_{j=1}^{3} \overline{M}_{ij} \cdot \overline{\omega}_j \right)$.

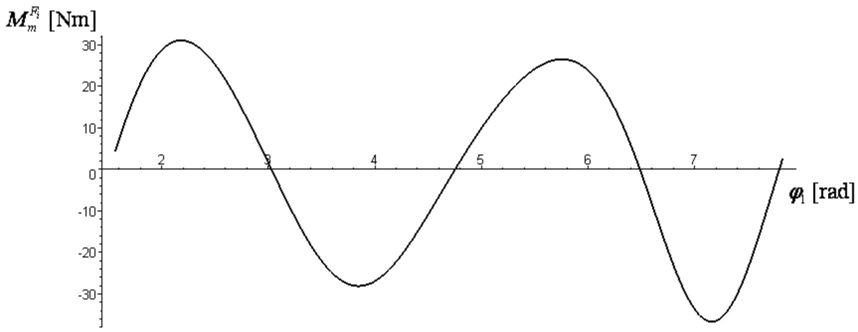

Figure 6. The variation of the moment $M_m^{F_i}$

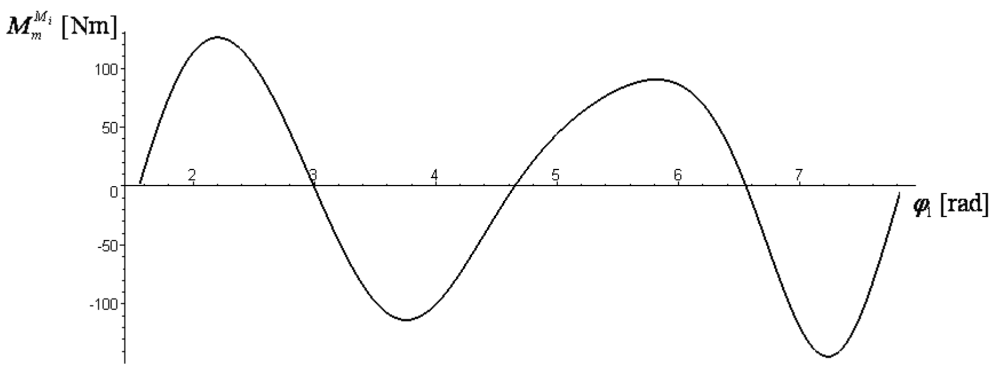

Figure 7. The variation of the moment $M_m^{M_i}$

CONCLUSIONS

In the paper has been presented a method for obtaining the variation during a cinematic cycle of the motor torque at the crankshaft in the case of the conventional sucker rod pumping units. A computer program which allows simulating the operation of the mechanism of the conventional sucker rod pumping units has been developed. The simulations results presented in the case of a C-640D-305-120 pumping unit showed that this one is well balanced. From the analysis of the contribution to the variation of the motor torque at the crankshaft resulted that most of it is due to the force at the polished rod and to the weight of the component elements, the influence of the inertia forces and inertia moments being negligible.

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