

# Simulation of the Sucker Rod Column Dynamics for Different Pumping Regimes

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*Proper functioning of the sucker rod pumping installations is strongly influenced by the sucker rod column dynamics and can be appreciated, as is well known and widely applied in practice, by the allure of the surface dynagraph. The paper presents some results concerning the simulation of the sucker rod column dynamics obtained with a computer program developed by the authors. The simulation results are compared with experimental results obtained at two pumping installations. Then, the computer program is used to study the sucker rod column dynamics for another pumping regime at one of analyzed installations.*

*Keywords: sucker rod column, dynamics, surface dynagraph, pumping regimes*

It is known that most of the oil production (over 85% [1]) is extracted by pumping, the sucker rod pumping installations being the most simple pumping system to use and the most efficient for wells that can no longer ensure an eruptive exploitation. Prediction with a great degree of precision of the performances of such installations during operation is extremely difficult because of the complex interactions that exist between components, with direct influence on their dynamic behavior. Therefore, development of study models to express as accurately as the dynamics of that pumping installations and then creation of some computer programs to allow the simulation of their operation for different operating conditions can lead to optimization of working processes and of the cost of production.

First researches concerning the sucker rod pumping installations that led to impressive results in their constructive and functional evolution dates back from the 70's of last century. These were distinguished by the achievements concerning the behavior of the sucker rod pumping systems during operation, the assessment of the loads due to the vibrations of the sucker rod column and the study of the mechanism of the pumping units [2-4]. Much of further research on the design and the behavior during operation of these installations focused mainly on the study of the dynamics of the sucker rod column and on issues related to the analysis and synthesis of the mechanism of the pumping units. In this respect, a number of interesting results that have strongly helped to the achievement of the research from this paper are presented in [5-9].

It is well known in practice that the proper functioning of the sucker rod pumping installations is strongly influenced by the sucker rod column dynamics and can be appreciated by the allure of the surface dynagraph, namely the variation of the force at the polished rod according to its displacement on a cinematic cycle. Establishing the surface dynagraph is necessary for specifying the variation cycle of the loads to the design of the pumping units and is very useful to the creation of a card index of standard surface dynagraphs as to constitute a basis for comparison with the dynagraphs acquired with the dynamometer for a more precise diagnostic of the equipment operation.

In this paper it is analyzed the dynamics of the sucker rod column and there are presented some simulation results obtained with a computer program developed by the

authors. Surface dynagraphs obtained by simulation are compared to those obtained experimentally at two pumping installations and then the computer program is used to study the sucker rod column dynamics at one of analyzed installations for another pumping regime.

## Experimental part

The experimental determinations were made at the wells Colibasi 256 and Tazlau 268 belonging to OMV Petrom. Measurement, experimental data acquisition and processing were performed with the equipment integrated in the system called echometer [1,10]. Dynamometer measurements were performed using the mounting scheme shown in figure 1.

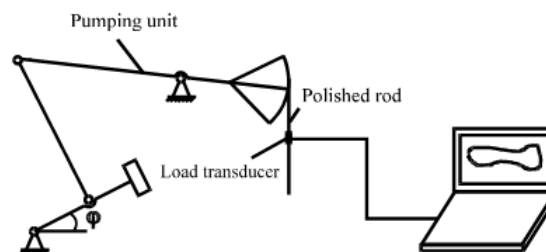


Fig. 1. Mounting scheme for dynamometer measurements

The well Colibasi 256 has a depth of 2240 m. The component of the sucker rod column is as follows: the first segment of 480 m has sucker rods of 1 in, the second segment of 480 m has sucker rods of 7/8 in and the third segment of 1280 m is composed of sucker rods of 3/4 in. The column of tubing has the following structure: the first segment of 1000 m has extraction pipes of 3.5 in and the second segment of 1240 m is composed of extraction pipes of 2.875 in. Extraction pump used is of type RHTC 25-125-20-4-0-0 having the piston diameter of 1.25 in. The well is served by a C-640D-365-144 pumping unit. The work angular speed of the cranks is of 4.71 rot/min.

In figure 2 it is shown the surface dynagraph measured for a cinematic cycle at the well Colibasi 256.

The well Tazlău 268 has a depth of 1025 m. The sucker rod column has two segments: the first segment of 436 m has sucker rods of 7/8 in and the second segment of 589 m is composed of sucker rods of 3/4 in. The column of tubing has the following structure: the first segment of 918 m has extraction pipes of 3.5 in and the second segment of 107 m is composed of extraction pipes of 2.875 in.

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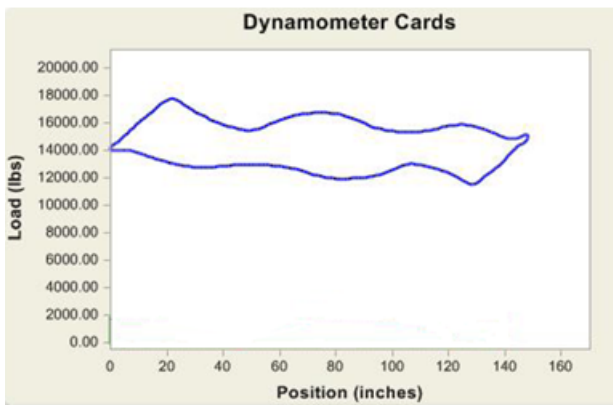


Fig. 2. Experimental surface dynamograph in the case of the well Colibasi 256

Extraction pump used is of type 25-175-RHBC-12-3-0-0 having the piston diameter of 1.75 in. The well is served by a C-1280D-427-192 pumping unit. The work angular speed of the cranks is of 6.5 rot/min.

The surface dynamograph measured for a cinematic cycle at the well Tazlau 268 is shown in figure 3.

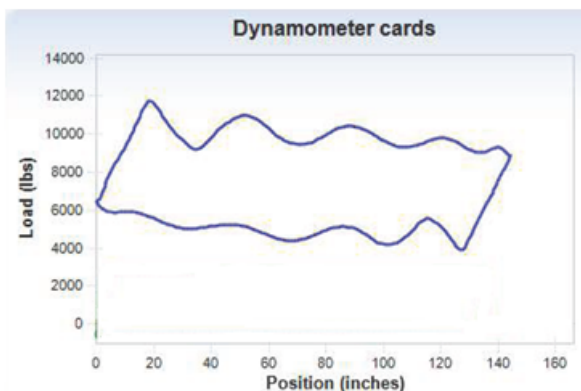


Fig. 3. Experimental surface dynamograph in the case of the well Tazlau 268

#### Establishing by calculation of the surface dynamograph

This calculation is done by considering the four basic phases of the operating cycle of a pumping installation [5]: I) the phase corresponding to the initial deformation of the sucker rods and of the extraction pipes at the beginning of the upward movement of the sucker rod column; II) the phase corresponding to the upward movement of the sucker rod column; III) the phase corresponding to the initial deformation of the sucker rods and of the extraction pipes at the beginning of the downward movement of the sucker rod column; IV) the phase corresponding to the downward movement of the sucker rod column after the initial deformation.

The force at the polished rod for the four phases of the operating cycle can be calculated with the following relations [5]:

$$F_I = G_i - F_f + k \cdot u(\varphi) + \frac{m \cdot a(\varphi)}{2}; \quad 0 < \varphi < \varphi_1 \quad (1)$$

$$F_{II} = G_i + G_b + F_f + F_i + F_v + F_o; \quad \varphi_1 < \varphi < \varphi_2 \quad (2)$$

$$F_{III} = G_i + G_b + F_f - k \cdot (S - u(\varphi)) + \frac{m \cdot a(\varphi)}{2}; \quad \varphi_2 < \varphi < \varphi_3 \quad (3)$$

$$F_{IV} = G_i - F_f + F_i + F_v + F_o; \quad \varphi_3 < \varphi < 2\pi \quad (4)$$

where:  $\varphi$  is the crank angle (fig. 1);  $u(\varphi)$ ,  $v(\varphi)$  and  $a(\varphi)$  are the displacement, the speed and the acceleration, respectively, of the end of the polished rod, the manner of

their determining depending on the dimensions of the component link of the pumping unit, the crank angle  $\varphi$  and the work angular speed of the cranks being presented in [3,8,9]. In [8,9] it is also presented the manner of determining the surface stroke  $S$  of the pumping unit and of the crank angle  $\varphi_a$  corresponding to the end of the upward movement of the sucker rod column;  $G_i$  is the weight of the sucker rod column when it is introduced into the oil:  $G_i = b \cdot G$  ( $b$  is the buoyancy factor:  $b = 1 - \rho_o / \rho_s$ , where  $\rho_o$  and  $\rho_s$  are the density of the oil and the density of the steel from which are made sucker rods, and  $G$  is the weight of the sucker rod column in air, which is calculated taking into account its composition and the weight per each section);  $G_b$  is the weight of the oil column, considered as acting on the gross surface of the piston of the depth pump;  $F_i$  is the force due to the friction of the piston into the depth pump and to the friction of the sucker rods into extraction pipes:  $F_i = 35 \cdot D$  [kN] where the piston diameter  $D$  is expressed in meters;  $F_o$  is the friction force into extraction pipes that occurs because of the transport of the oil therethrough:

$$F_o = \frac{\rho_o}{2} \cdot \lambda \cdot \frac{A_p}{d_t} \cdot \left( \frac{A_p}{A_t} \right)^2 \cdot L \cdot v^2 \quad (5)$$

where:  $\lambda$  is the hydraulic loss coefficient (it can be considered  $\lambda = 0.046$ , that is a typical value for rough pipes [5]);  $A_p$  is the net sectional area of the piston;  $A_t$  is the interior passage sectional area of the extraction pipes;  $L$  is the length of the sucker rod column and  $v$  is its speed;  $F_o$  is the force due to the free oscillations of the sucker rod column that occur when changing the conditions from phase I to phase II and from phase III to phase IV. When changing the conditions from phase I to phase II,  $F_o$  can be calculated with the relation [5]:

$$F_o = e^{-\frac{t-t_1}{\alpha}} \cdot \frac{p \cdot m \cdot \psi}{2} \cdot v_1 \cdot \sin p \cdot (t - t_1) \quad (6)$$

where:  $t_1$  is the time corresponding to the crank angle  $\varphi_1$ ;  $p$  is the pulsation of intrinsic oscillations of the sucker rod column (it can be calculated with the formula [5]:  $p = 8000 / L$ );  $m$  is the total mass of the sucker rods;  $v_1$  is the speed of the polished rod when the crank angle is equal to  $\varphi_1$ ;  $\alpha = 0.2 \cdot T$ ; ( $T$  is the period of the pumping cycle);  $\psi = k_p / (k_p + k_t)$  where  $k_p$  and  $k_t$  are the elastic constants corresponding to the sucker rod column and to the extraction pipes column, respectively:

$$\frac{1}{k_p} = \sum_i \frac{1}{k_{pi}} \quad (7)$$

$$\frac{1}{k_t} = \sum_i \frac{1}{k_{ti}}$$

where:  $k_{pi}$  and  $k_{ti}$  are the elastic constants corresponding to the section  $i$  of the sucker rod column and to the extraction pipes column, respectively:

$$k_{pi} = \frac{EA_{pi}}{l_{pi}} \quad (8)$$

$$k_{ti} = \frac{EA_{ti}}{l_{ti}}$$

where:  $E$  is Young's modulus of the steel from which are made the sucker rods and the extraction pipes;  $l_{pi}$  and  $l_{ti}$  are the length of the section  $i$  of the sucker rod column and of the extraction pipes column, respectively, and  $A_{pi}$  and  $A_{ti}$  are the corresponding sectional areas. The relation for the calculus of  $F_o$  when changing the conditions from phase III to phase IV is analogous to (6), in which the time  $t_1$  is

replaced by  $t_2$  corresponding to the crank angle  $\varphi_2$  and the speed  $v_1$  with  $v_2$  which is the speed of the polished rod when the crank angle is equal to  $\varphi_2$ ;  $F_i = m \cdot a(\varphi)$ ; is the force due to the inertia of the sucker rods;  $\varphi_1$  is the value of the crank angle  $\varphi$  corresponding to the end of the first phase. It can be calculated by solving the following equation [5]:

$$u(\varphi) = \frac{G_s + 2F_f}{k} \quad (9)$$

where  $k$  is the elastic constant of the system composed by the sucker rods and extraction pipes:

$$\frac{1}{k} = \frac{1}{k_p} + \frac{1}{k_t} \quad (10)$$

If the extraction pipes are anchored at the lower end to the exploitation column then:  $k = k_p$  [5]. The crank angle  $\varphi_2$  corresponding to the end of the third phase of the operating cycle has the value given by the following relation [5]:  $\varphi_2 = \varphi_1 + \pi$ .

By applying the relations (1)÷(4) it is obtained the variation on a cinematic cycle of the force  $F$  at the polished rod depending on the crank angle  $\varphi$ . Having the variation curves  $F(\varphi)$  and  $u(\varphi)$  on a cinematic cycle, then can be obtained the surface dynagraph.

### Simulation results and discussions

The calculus algorithm presented hereinbefore has been transposed by the authors into a computer program using Maple programming environment [11]. The computer program allows determining among other of the variation curves on a cinematic cycle of the displacement  $u(\varphi)$ , of the speed  $v(\varphi)$  and of the acceleration  $a(\varphi)$  of the end of the polished rod and also of the variation on a cinematic

cycle of the force  $F$  at the polished rod depending on the crank angle  $\varphi$  and of the surface dynagraph. In figures 4 and 5 there are superposed the measured surface dynagraphs and those obtained by simulation in the case of the wells Colibasi 256 and Tazlau 268.

Figures 4 and 5 reveal a good correlation between the experimental results and those obtained by analyzing the complex phenomena that appear in the modeling of the dynamics of the sucker rod column. One of the causes of the differences are due to the complex phenomena of friction occurring between the sucker rods and the extraction pipes, between the piston and the cylinder of the depth pump and between the sucker rod column and the extraction pipes column on the one hand and the oil on the other hand.

For a rational use of the sucker rod pumping installations, to prevent excessive oscillations of the sucker rod column and their premature fatigue, is recommended the static pumping regime [1,5]. In order that a pumping installation operates in static regime, in practice it is used for determining the maximum permissible angular speed of the cranks the following relation [5]:

$$\omega < \frac{2000 \dots 2300}{H} \quad [\text{rad/s}] \quad (11)$$

where  $H$  is the depth of the well. By considering the well Colibasi 256, in which case  $H = 2240$  m, it results  $\omega < 0.9$  rad/s or by expressing in rotations per min:  $n < 8.6$  rot/min.

It has been analyzed the case when the installation of the well Colibasi 256 works at the limit of the static regime with  $n = 8$  rot/min.

In figure 6 is presented the variation on a cinematic cycle of the force  $F$  at the polished rod depending on the crank angle  $\varphi$  (starting with the crank angle corresponding to the beginning of the upward movement of the sucker rod

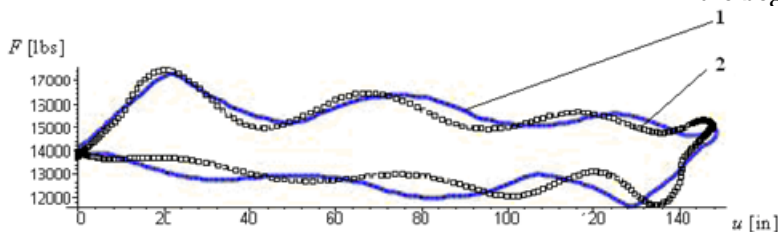


Fig. 4. Experimental surface dynagraph (curve 1) and the surface dynagraph obtained by simulation (curve 2) in the case of the well Colibasi 256

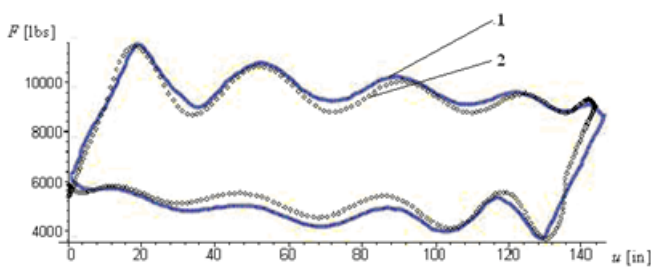


Fig. 5. Experimental surface dynagraph (curve 1) and the surface dynagraph obtained by simulation (curve 2) in the case of the well Tazlau 268

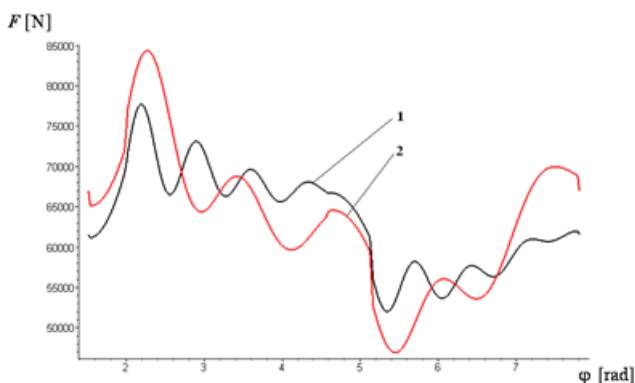


Fig. 6. The variation on a cinematic cycle of the force at the polished rod for  $n = 4.71$  rot/min (curve 1) and for  $n = 8$  rot/min (curve 2) in the case of the well Colibasi 256

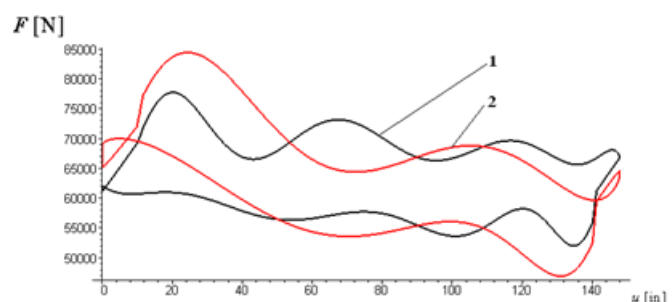


Fig. 7. The surface dynagraphs for  $n = 4.71$  rot/min (curve 1) and for  $n = 8$  rot/min (curve 2) in the case of the well Colibasi 256

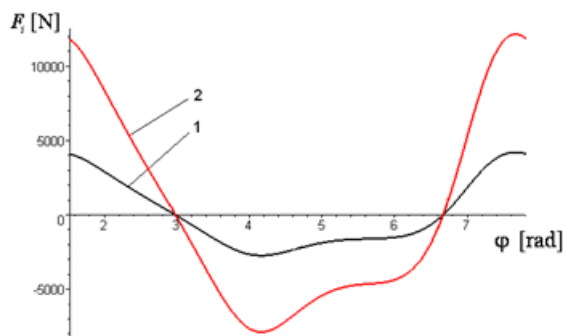


Fig. 8. The variation of the force  $F_i$  for  $n=4.71$  rot/min (curve 1) and for  $n=8$  rot/min (curve 2) in the case of the well Colibasi 256

column, which in this case is of 1.528 rad) for the two cases, that of the functioning when  $n=4.71$  rot/min (curve 1) and when the installation works at the limit of the static regime with  $n=8$  rot/min (curve 2). Figure 7 presents the surface dynagraphs in these two cases.

Figures 6 and 7 highlight a significant increase of the maximum value of the force at the polished rod when the installation works at the limit of the static regime. From the two figures it also can be noticed that in the second case when  $n=8$  rot/min the difference between the extreme values of the force at the polished rod is much higher than when  $n=4.71$  rot/min, which leads to a more pronounced dynamic load of the sucker rod column.

From the analysis realized with the computer program mentioned before of all components involved in calculating the force at the polished rod it was seen an important increase of the values of the force  $F_i$  due to the inertia of the sucker rods (fig. 8) and of the force  $F_o$  due to the free oscillations of the sucker rod column that occur when changing the conditions from phase I to phase II (fig. 9) when the installation works at the limit of the static regime. The variation curves in figure 8 have been represented on a cinematic cycle starting with the crank angle corresponding to the beginning of the upward movement of the sucker rod column and those in figure 9 for  $\varphi \in a[\varphi_1, \varphi_a]$ , where  $\varphi_1=2.24$  rad and  $\varphi_a 4.604$  rad.

## Conclusions

The main purpose of the research conducted by the authors and presented in this paper was to develop a computer program with which it can be simulated the dynamics of the sucker rod column for different work regimes. The results obtained with this computer program have been revealed a good correlation with the experimental results. Therefore, it is an extremely useful tool for analyzing and modeling the complex phenomena that appear during the movement of the sucker rod column and especially for obtaining the variation on a cinematic

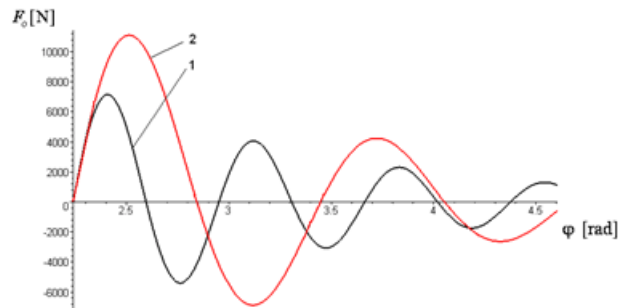


Fig. 9. The variation of the force  $F_o$  for  $n=4.71$  rot/min (curve 1) and for  $n=8$  rot/min (curve 2) in the case of the well Colibasi 256

cycle of the force at the polished rod depending on the crank angle and of the surface dynagraph.

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