Semi-natural simulation system of a sucker-rod pump

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Abstract. This article describes the development of a semi-natural torque load simulation system on an induction motor shaft that simulates the operation of a sucker-rod pump (SRP). For semi-natural simulation, a laboratory bench with an induction motor (IM) and direct current motor located on the same shaft is used. The four-link mechanism kinematic scheme of a sucker-rod pump and the implementation of software modules for calculating load torque are presented. The main results of simulation tests are given.

1. Introduction and problem statement

The pumpjack, as a four-link mechanism with its kinematic ratios, is difficult to analytically calculate the forces arising in its elements. In many cases, the coordinates of suspension point of the rod string is considered as harmonic [1], which in practice led to significant errors in the calculations of the applied forces and torques. For more accurate analysis of the pumpjack’s elements internal forces, it is often better to use simulation or semi-natural modeling.

Therefore, it is proposed to develop and use a special load system that simulates the forces during the operation of a sucker rod pump (SRP). The load torque is formed using the direct current motor (DCM), which is placed on the same shaft with the induction motor (IM), which simulates SRP prime mover.

The laboratory bench is based on hardware-in-the-loop (HIL) simulation technique using the frequency converter with open software platform mbs-fc01 [2] with MexBIOS Development Studio which is development and simulation/emulation software in the field of electric drive.

Semi-natural simulation system aims to achieve DCM electro dynamic torque that is similar with the torque on the input gearbox shaft during the operation of a SRP. Briefly consider the vector control system operation of an electric drive and the dynamogram of the SRP operation.

2. Main part

With field-oriented vector control of IM, it is possible to determine the electrodynamic torque by a projection of the stator current [2, 3]:

$$T_e = \frac{3 \cdot Z_p \cdot \psi_R \cdot I_{sq}}{2},$$

where $Z_p$—the number of motor pole-pairs; $\psi_R$—the modulus of a rotor flux vector; $I_{sq}$—the stator projection on the $q$ axis.
The load torque on the motor shaft can be obtained from the equation of dynamics of the mechanical part of the electric drive:

\[ T_L = T_r - (J \frac{d\omega}{dt} + C \cdot \omega), \]  
(2)

where \( J \) – the inertia; \( \omega \) – mechanical rotor speed; \( C \) – friction coefficient; \( T_L \) – load torque of resistance on the IM shaft.

It is also possible to express the load torque on the IM shaft as:

\[ T_L (\omega) = T_w + \frac{T_c (\omega)}{i}, \]  
(3)

where \( T_w \) – the IM constant torque necessary for gear rotation; \( i \) – gear box ratio.

According to the kinematic scheme of pumpjack (Fig. 1), it is determined that the torque on the output shaft of the gearbox can be written as:

\[ T_C = T_\alpha + T_{cw} + T_{J\Sigma}, \]  
(4)

where \( T_\alpha \) – load torque from the force that acts at the rod string suspension point; \( T_{cw} \) – load torque from counterbalance, \( T_{cw} = T_w R \sin(\theta) \), \( T_w \) – maximum load counterbalance torque; \( T_{J\Sigma} \) – total load torque from the inertial forces including reciprocating (from walking beam, equalizer, pitman) and rotating masses inertia.

![Figure 1. The kinematic scheme of a pumpjack.](image)

In the case of constant rotation speed of the crank, the inertia torque will be zero, the reciprocating inertia will be negligibly small. Thus, we can write:

\[ T_C = T_\alpha + T_{cw}. \]  
(5)

The torque due to the action of the counter weight for equation (5) is found from the kinematic relations of the pumpjack (Figure 1):

\[ T_\alpha = \frac{RA \sin \alpha}{C \sin \beta} (F_\alpha - F_{CU}), \]  
(6)

where

\[ \alpha = \varphi - \theta + \beta + \psi, \]  
(7)

\[ \beta = \arccos \left( \frac{C^2 + B^2 - J^2}{2BC} \right), \]  
(8)
\[ \psi = \begin{cases} \epsilon - \xi, & \sin(\theta - \varphi) \geq 0 \\ \epsilon + \xi, & \sin(\theta - \varphi) < 0 \end{cases}, \quad (9) \]

\[ \epsilon = \arccos \left( \frac{C^2 + J^2 - B^2}{2CJ} \right), \quad (10) \]

\[ \xi = \arccos \left( \frac{K^2 + J^2 - R^2}{2KJ} \right), \quad (11) \]

\[ J = \sqrt{R^2 + K^2 - 2RK \cos(\theta - \varphi)}, \quad (12) \]

\[ K = \sqrt{L_2^2 + L_3^2}. \quad (13) \]

The constructive unbalance \( F_{CU} \) determined the additional force for balancing the walking beam \[4\].

Further consider the implementation of the load torque model in the MexBIOS environment and briefly describe the main functional blocks.

![Figure 2. Main program flowchart.](image_url)

The general flowchart of the program is shown on in the Figure 2. The program block “Load” (Figure 3) of the flowchart performs calculation of the SRP dynamogram.

The program block algorithm uses the multiplexer block, which selects one of two functions, depending on the sign of rod string suspension point velocity that is, depending on the direction of the plunger movement up or down. As a result of the algorithm, the force at rod string suspension point \( F_3 \) was obtained.

The “Calculator” block is intended to calculate the torque \( T_C \) on the output shaft of the gearbox using (5) and (6) equations with kinematic parameters of the pumpjack obtained from “Const” block.
The DCM closed loop current regulator is synthesized on desired transfer function in form of aperiodic link to implement the torque reference of semi-natural model on the basis of the laboratory bench. Thus, by setting the DCM current in proportion to the calculated torque, a load is performed on the IM shaft, simulating the forces arising during the operation of the SRP. This solution is implemented in the MexBIOS visual programming environment.

![Diagram](image)

**Figure 3.** «Load» block program code.

3. Results

The simulation results in the MexBIOS software environment are presented in figures 4 and 5.

![Graph](image)

**Figure 4.** Calculated dynamogram of simulated SRP.

In figure 4 section 1 – corresponds to the force at the time of expansion of the rod string before the plunger moves up, section 2 – movement up of the plunger, section 3 – the force at the moment of compression of the rod string before the plunger moves down, section 4 – movement down of the plunger.
Figure 5 shows the torque \( T_c \) on the output shaft of the gearbox, which consists of the torque \( T_{cw} \) due to the action of the gravity of the counterweight, and the torque \( T_\lambda \) due to the force \( F_\lambda \) arising at the point of suspension of the rod string [4, 5].

\[ T_{cw}, T_c, T_\lambda \]

Figure 5. Torques that arise during the operation of the SRP.

Where \( T_\lambda \) – load torque from the force that acts at the rod string suspension point; \( T_{cw} \) – load torque from counterbalance; \( T_c \) – the torque on the output shaft of the gearbox.

This model provides useful information about the design and operation of a sucker-rod pump. The semi-natural load model developed at the laboratory bench is planned to be used for further design and research of various SRP electric drive systems, including the development of the most promising sensorless control.

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