Model Reference Adaptive Control Applied to the Improvement of the Operational Conditions of a Sucker Rod Pump System

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Abstract: Several studies have shown that the satisfactory operation of oil wells with sucker rod pumps is attributed to the techniques and methods able to control the performance of the well. The Polytechnic School of Federal University of Bahia, through the Artificial Lift Lab, has nowadays a reduced plant of a sucker rod pump with an artificial well of 32m height fully instrumented, with full access and visible. Among some studies already performed with this sucker rod pump, there is the use of a dynamic model to control the fluid level in annular well. The presence of uncertainties is related to the fluid characteristics in the well, associated with either the electrical or the mechanical assembly, may jeopardize the desired performance of the PID controller. These uncertainties usually do not contribute to good results and may put in risk the well's productivity. The aim of this paper is to show a model reference adaptive controller to deal with some uncertainties in the system model to control the level of the annular well. The results show that the adaptive controller is able to deal satisfactorily with changes, such as: in the pumped fluid composition (parts of water, oil and gas), which is a very common situation in real production fields.

1. INTRODUCTION

The rod sucker pump system is the artificial lift method most used in the current on-shore petroleum industry due to the simplicity of its equipments and installations (Barreto Filho, 2001). This method is also considered as the first technique used to lift oil up from wells. Studies show that its popularity is related to low costs of investments and maintenance, deep and outflow flexibility, good energy efficiency and the possibility for operating in different fluid compositions and viscosities in a wide range of temperature (Takács, 2002)**.**

Although this lift method is already well-known and widely used, there are some opportunities of improving the operational conditions, especially, to deal with production control strategies of the pump unit for increasing the system productivity and reducing the maintenance costs. The development of low cost downhole fiber optic sensors turned possible the measurement of downhole variables that assists the production monitoring and the application of new control strategies (Bezerra *et al.*, 2009), (Moisés *et al.*, 2008), (Smith *et al.*, 2008). In this context, The Polytechnic School of Federal University of Bahia, through the Artificial Lift Lab (LEA), has nowadays a reduced plant of a sucker rod pump with an artificial well of 32m of height fully instrumented, with full access and visible. All components of this sucker rod pump system are industrial and the plant also has a supervisory system to data acquisition and control.

A kind of operational problem with simultaneous impacts on productivity and the maintenance costs is the fluid pound (Bommer and Shrauner, 2006), (McCoy *et al.*, 2003). The fluid pound occurs when the downhole pump is filled short, or instead when the pumping capacity exceeds the reservoir production, or also when the fluid level in the annular well is insufficient for full pump filling. This situation causes a reduction of the effective plunger displacement and, therefore, loss of production. This problem is associated with the increase in operational costs for repairing the downhole pump equipment.

However, in terms of production control of the pump unit, the presence of some uncertainties in parameters in the dynamic system model may jeopardize the good performance of a conventional controller (e.g.: PID). These uncertainties, in the case of the sucker rod pump, normally are related to or fluid characteristics in the well either associated with the electrical and mechanical assembly.

The aim of this paper is to use a Model Reference Adaptive Control (MRAC) to deal with some uncertainties in the system model to the control of the fluid level in the annular well. Moreover, MRAC may also deal the fluid pound occurrence avoiding negative effects, such as, parameters uncertainties and process changes. These effects may risk the satisfactory operation of the pump controller directly associated with the pump filling and with effects in the system oil productivity.

2. THE SUCKER ROD PUMP SYSTEM

2.1 System Description

In this artificial lift method a rotatory movement of or an electric motor either combustion motor localized on surface of the pump unit is converted in alternative movement of the rods column. This same column transmit the alternative movement to the pump components that are located in downhole well, that are responsible to elevate the fluid from reservoir to the surface. The sucker rod pump system could be divided in downhole and surface elements, (see Fig. 1).

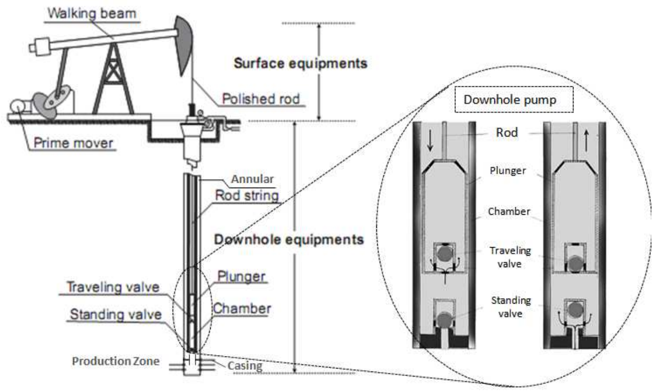

Fig. 1. Components of a rod sucker pump system.

The rods column is the link between the pump unit localized on the surface and the downhole pump. The downhole pump is a kind of alternative pump of positive displacement and simple effect, in other words, the fluid is displaced in a one way direction of the alternative movement. The function of the downhole pump is to provide energy (increasing the pressure) to the fluid from reservoir. (Thomas *et al*., 2001)

2.2 Operational Aspects of the Sucker Rod Pump System

The fluid pound has an influence on the oil production and the maintenance costs. This phenomenon occurs when the annular level is insufficient for the complete pump filling of plunger chamber during the up-stroke cycle, A in the Fig. 2. In abnormal situation, at the beginning of the down-stroke cycle, the traveling valve is opened when exists contact with the fluid column presents in the plunger chamber, whose pressure allows a soft discharge of the pump. However, if the chamber was not completely filled, the plunger finds a gas column, in B, whose low pressure is not enough for opens the traveling valve. The advance of the plunger, at some moment, will suddenly find the fluid column in the plunger interior, in C, what it goes to cause a strong transference of the load, and therefore, a strong mechanical impact on the pump components (Ordoñez *et al*., 2008).

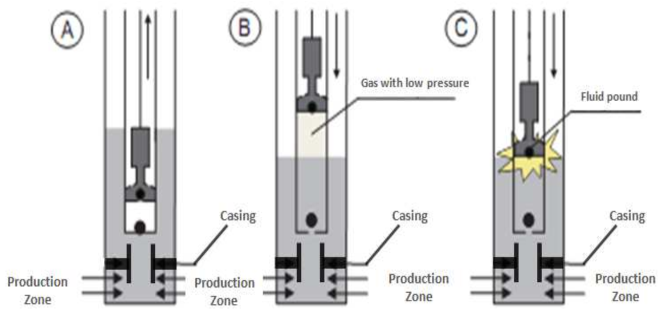

Fig 2. The fluid pound phenomenon

2.3 The Fluid Dynamic Model in the Annular Well

The production performance of a rod sucker pump system is directly associated with fluid level in annular well. Thus, it is necessary to obtain the fluid-level-dynamic-model in annular well and his relationship with some of variables of entire system. As follow in Fig. 3.

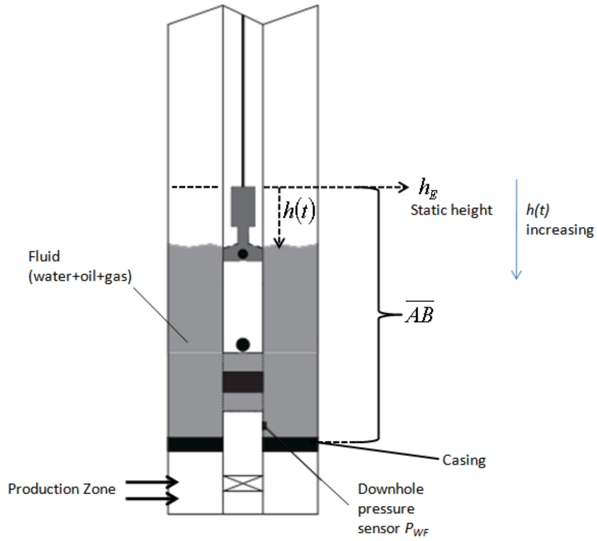

Fig. 3. Downhole well scheme with sucker rod pump system.

It is possible to obtain the volumetric balance given by an ordinary differential equation of the drainage of the annular well as follow in (1)

$$Q_{AN}(t)+Q_R(t)=Q_B(t). \tag{1}$$

Where $Q_R(t)$ is the outflow from the reservoir to the annular well, $Q_{AN}(t)$ is the outflow from the annular well to the production well (where is localized the downhole pump) and $Q_B(t)$ is the downhole pump outflow. The outflow from the annular well to the production well $Q_{AN}(t)$ is given by

$$Q_{AN}(t)=A_{AN}\dot{h}(t). \tag{2}$$

Where $\dot{h}(t)$ is the level ratio of the $h(t)$ in the annular well and A_{AN} is the transversal section area of the annular. The annular area is calculated as follow: $A_{AN}=\frac{\pi}{4}\left((D_{INT}^{CAS})^2-(D_{EXT}^{PROD})^2\right)$. Where D_{INT}^{CAS} is the internal diameter of the casing pipe, D_{EXT}^{PROD} is the external diameter of the production well. The outflow from the reservoir to the annular well $Q_R(t)$ is given by

$$Q_R(t)=PI(P_S-P_{WF}(t)). \tag{3}$$

Where PI is called Productivity Index, P_S is the static pressure and is the static pressure and P_{WF} is the well flowing pressure (also called downhole pressure). Equation (3) is also called Inflow Performance Relationship (IPR) in which the outflow $Q_R(t)$ varies linearly with the downhole pressure P_{WF}. Figure (4) shows the IPR graph

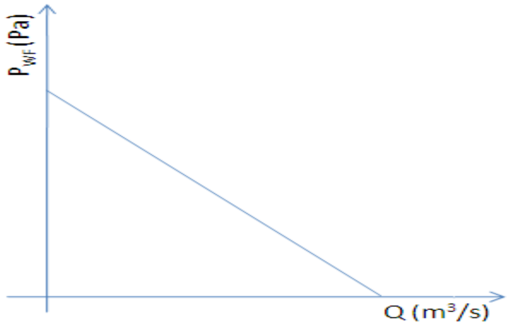

Fig. 4 The IPR graph

The static pressure P_S is given by

$$P_S = P_{CAS}^S + \gamma_F \overline{AB} . \tag{4}$$

Where P_{CAS}^S is the casing pressure in statics conditions (the pump system is down and there is no production), γ_F is the specific weight of the fluid (that may be a composition of water, oil and gas), $\overline{AB}$ is length between the static level h_S and the casing. In this work the pressure of the gas column on the fluid level in annular well will not take in count. The reference point is the point where h_S occur. The well flowing pressure P_{WF} is given by

$$P_{WF}(t) = P_{CAS}^D + \gamma_F [\overline{AB} - h(t)] . \tag{5}$$

Where P_{CAS}^D is the casing pressure in dynamics conditions (the pump system is on and there is production) and $h(t)$ is the level as indicated in Fig. 3 in the time *t*. It will be assumed here $P_{CAS}^S \cong P_{CAS}^D$

$$A_{AN}\dot{h}(t) + IP\gamma_F h(t) = Q_B(t) . \tag{6}$$

Equation (6) could be rewritten (6) as follow in (7)

$$\dot{h}(t) = -\frac{PI\gamma_F}{A_{AN}} h(t) + \frac{1}{A_{AN}} Q_B(t) . \tag{7}$$

It could be observed that the dynamic model in (7) is a linear relationship given by first order ordinary differential equation.

3. THE CONTROL TECHNIQUE

3.1 System Description

The Model Reference Adaptive Control (MRAC) is one of main techniques in adaptive control. The changes in the controller parameters are provided by the adjustment mechanism with the objective to minimize the error between the system under control and a model reference output (that is the desired response). MRAC uses integral laws to adaptation and this makes a slow and oscillatory transitory, but in steady state there is a soft control signal (Narendra and Valavani, 1978; Aström & Wittenmark, 2008).

The block diagram in Fig. 5 may explain the idea of a system using MRAC.

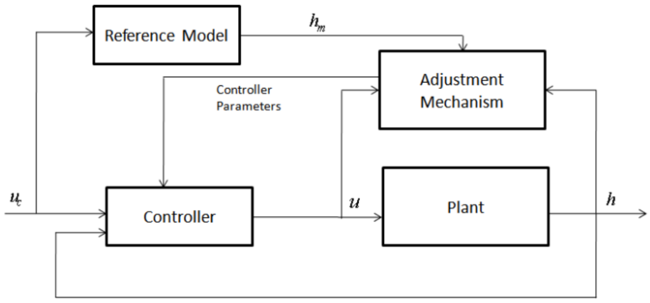

Fig. 5. Block diagram of MRAC

3.2 MRAC Applied to the Sucker Rod Pump System

The systems that are used sucker rod pumps, most of time is desired that the operation point is next to the pump suction level. This operation point is characterized by the complete pump filling with the minor P_{WF} possible, which provides a minor against pressure in the production zone of the reservoir, and, in turn, increases the oil production (Ordoñez *et al*., 2008).

In this work MRAC classical technique using Lyapunov's theory (Aström and Wittenmark, 2008) is applied to a sucker rod pump. It could be also desired that the controller operates near the point with the minor P_{WF} possible, in order to increase the oil production, without the occurrence of the fluid pound. Moreover, the controller must be able to adapt its parameters in case of process changes and uncertainties in the system model.

The desired response given by a model reference signal could be written as follow

$$\dot{h}_m = -a_m h_m + b_m u_c . \tag{8}$$

Where a_m and b_m are constant values and $a_m > 0$. The variable $h_m = h_m(t)$ is the desired response (in this case here is the level value) and the input signal $u_c = u_c(t)$ is bounded. The plant could be described as follow in

$$\dot{h} = -ah + bu . \tag{9}$$

Where *a* e *b*are or the plant unknown parameters either plant parameters with uncertainties. The variable *h* = *h(t)* is the measured output. The control law $u = u(t)$ is given by

$$u = \theta_1 u_c - \theta_2 h . \tag{10}$$

Where $\theta_1 = \theta_1(t)$ and $\theta_2 = \theta_2(t)$ are the controller parameters and they will be adapted. The error equation *e* = *e(t)* is set as

$$e = h - h_m . \tag{11}$$

Since we are trying to make the error small, it is natural to derive a differential equation for the error

$$\dot{e} = -ah + bu + a_m h_m - b_m u_c . \tag{12}$$

By substituting (10) and (11) in (12), one gets

$$\dot{e} = -a_m e - (b\theta_2 + a - a_m)h + (b\theta_1 - b_m)u_c . \tag{13}$$

The exact values for θ_1 and θ_2 to make (11) and (13) equal to zero are

$$\theta_1 = \frac{b_m}{b} \tag{14}$$

$$\theta_2 = \frac{a_m - a}{b}\,. \tag{15}$$

To construct a structure for adaptation to drive the parameters θ_1 and θ_2 to exact values in (14) and (15), it could introduce a quadratic function as follow

$$V(e,\theta_1,\theta_2) = \frac{1}{2}[e^2 + \frac{1}{\alpha}(b\theta_2 + a - a_m)^2 + \\ + \frac{1}{\alpha}(b\theta_1 - b_m)^2]. \tag{16}$$

Where γ is called adaptation gain and $\gamma > 0$.

Equation (16) is zero when the error e is zero and the controller parameters are equal to the exact values given by (14) and (15). We can define V as a candidate function of Lyapunov. To qualify V as a Lyapunov function the derivative $\dot{V}(t)$ must be negative. The derivative from (16) is

$$\dot{V}(t) = e\dot{e} + \frac{1}{\alpha}(b\theta_2 + a - a_m)\dot{\theta}_2 + \frac{1}{\alpha}(b\theta_1 - b_m)\dot{\theta}_1. \tag{17}$$

By substituting (13) in (17) one gets

$$\dot{V}(t) = -a_m e^2 + \frac{1}{\alpha}(b\theta_2 + a - a_m)(\dot{\theta}_2 - \alpha h e) + \\ + \frac{1}{\alpha}(b\theta_1 - b_m)(\dot{\theta}_1 + \alpha u_c e)\,. \tag{18}$$

If the adaptive laws are chosen as follow

$$\dot{\theta}_1 = -\alpha u_c e \tag{19}$$

$$\dot{\theta}_2 = \alpha h e\,. \tag{20}$$

By substituting (19) and (20) in (18), one obtains

$$\dot{V}(t) = -a_m e^2\,. \tag{21}$$

The derivative of $V(t)$ with respect to time is thus semi-definite negative, but not negative definite. This implies that $V(t) \le V(0)$ and therefore that e, θ_1 and θ_2 must be bounded. Finally this implies that the signal of $h = e + h_m$ also is bounded. We can derivate (21) with respect to time and use (13)

$$\ddot{V}(t) = -2a_m e\dot{e} \tag{22}$$

$$\ddot{V}(t) = -2a_m e[-a_m e - (b\theta_2 + a - a_m)h + (b\theta_1 - b_m)u_c]\,. \tag{23}$$

Since u_c, e and h are bounded, it follows that $\ddot{V}(t)$ is bounded. The derivative $\dot{V}(t)$ is thus uniformly continuous. From the Boundedness and convergence set theorem, if $\dot{V}(t)$ is uniformly continuous, then $e \to 0$ when $t \to \infty$. The proof of this theorem could be found in Khalil (1996) and is called as Barbalat's lemma.

4. SIMULATIONS AND ANALISYS RESULTS

The Matlab Simulink was used to simulate the proposed controller for the level control of the fluid in the annular well of the sucker rod pump in the present work. The block diagram designed in Simulink is shown in Fig. 6.

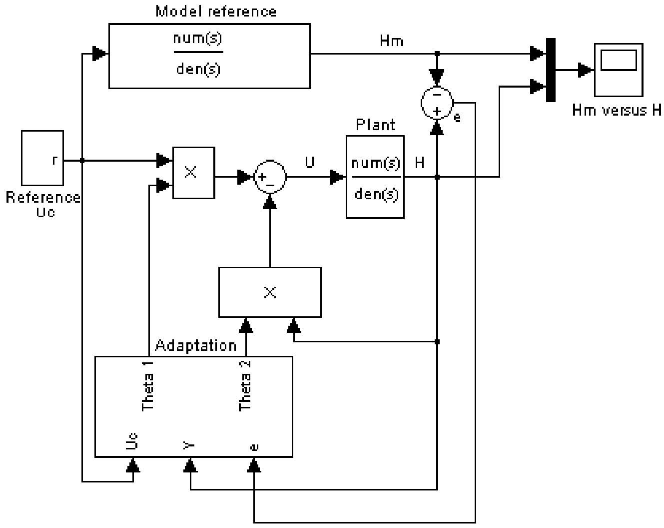

Fig. 6. Block diagram in Simulink.

The transfer functions of the plant and the reference model are, respectively

$$P(s) = b\frac{1}{s+a} \Rightarrow b = 56;\ a = 3 \tag{24}$$

$$M(s) = b_m\frac{1}{s+a_m} \Rightarrow b_m = 62{,}1;\ b_m = 3.1\,. \tag{25}$$

The data used here were obtained from real tests with the sucker rod pump system (physical system) in the LEA. The values to the reference model are: $PI = 4.96527 \times 10^{-9}\, m^3 s^{-1} Pa$, $A_{AN} = 0.0161\mathrm{m}^2$ and $\gamma_F = 9800 Nm^{-3}$. The values to the plant used in simulation of a situation where the values of IP, A_{AN} and γ_F are made different from those of the reference model to test the design and stability of the adaptive controller: $IP = 5.56243 \times 10^{-6}\, m^3 s^{-1} Pa$, $A_{AN} = 0.0178\mathrm{m}^2$ and $\gamma_F = 9600 Nm^{-3}$.

The simulations were performed regarding u_c (reference) as a square wave signal with amplitude equal to 1 and the adaption gain γ equal to 2.5. Fig. 7 shows the compared response between the model reference output and the plant output. Fig. 8 and Fig. 9 show the error signal and the control effort, respectively. Finally, Fig. 10 and Fig. 11 shows the parameters variations θ_1 and θ_2 with respect to time, respectively.

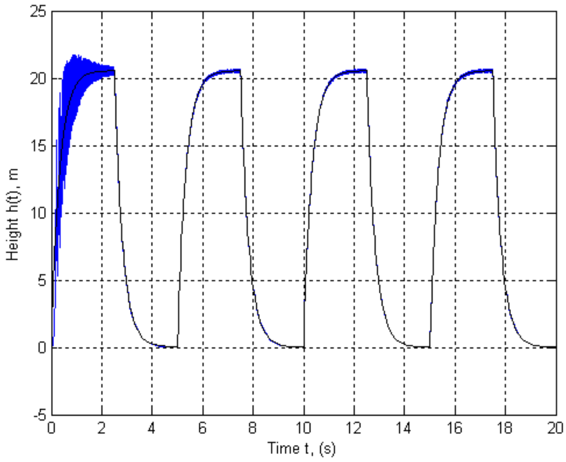

Fig. 7. Comparison between the desired response (model reference signal) and plant response.

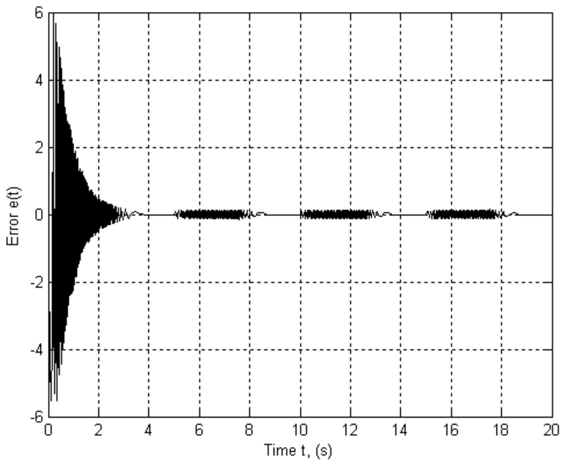

Fig. 8. Error signal.

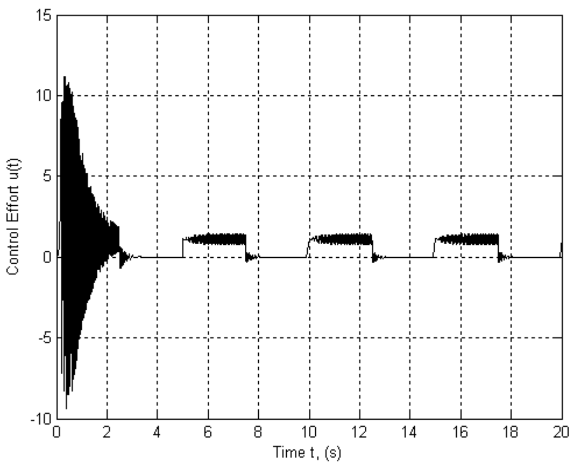

Fig. 9. Control effort.

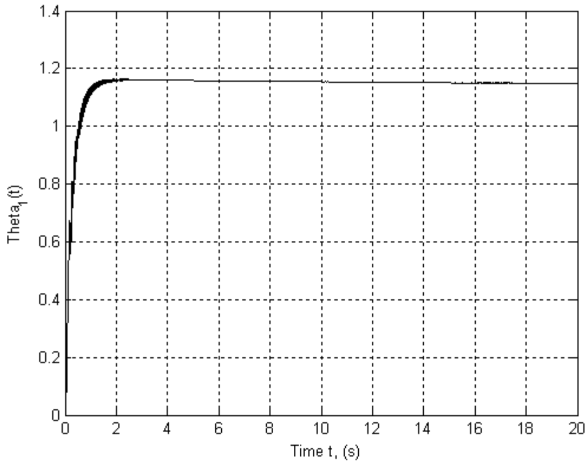

Fig. 10. Adaptation of θ_1.

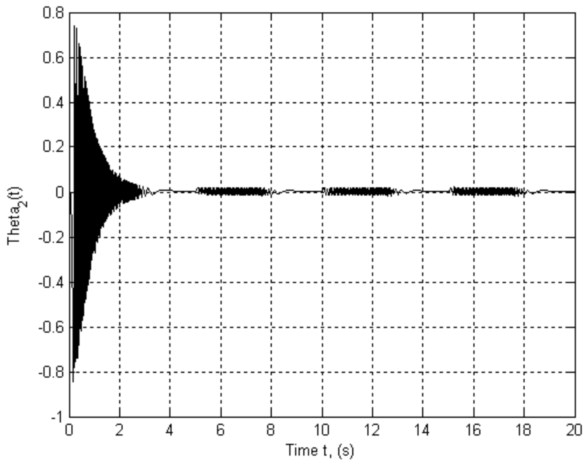

Fig. 11. Adaptation of θ_2.

According to (7) the reference signal u_c to be tracked is the downhole pump outflow $Q_B(t)$ $Q_B(t)$(that is the manipulated variable). It could be observed in Fig. 7 that the model reference output given by (7) was tracked by the plant output. The process variable $h(t)$ that is the fluid level in annular well could be observed in Fig. 7 with oscillations in transitory, but stable in steady state. The error e in steady state is little according to Fig. 8 and the control effort associated with downhole pump outflow is bounded and with little amplitude in Fig. 9 after some oscillations due to the effort in the parameter adaptation as could be seen in Fig. 10 and Fig. 11. Since the MRAC uses integral laws to the adaptation, one could observe a slow and oscillatory transitory in Fig. 7-9 and Fig. 11(Narendra and Valavani, 1978). An alternative to minimize or even cancel this oscillation in the transitory was presented in Torres and Schnitman, (2010). A new scheme based on variable structure and adaptive control with indirect approach (called IVS-MRAC) was applied over the sucker rod pump presented here.

5. CONCLUSIONS

In this paper the MRAC technique was applied in order to improve the operational conditions of a sucker rod system of petroleum wells. It could be observed through the simulations and analysis results that the desired response (output signal of the model reference) was tracked by the plant response. As a consequence of the parameters convergence to their exact values, the error signal could be seen bounded and near to zero and the control effort could be seen also bounded. The results show that the adaptive controller is able to control satisfactorily the fluid level in the annular well of the sucker rod pump system, in spite of the presence of model uncertainties or some process changes. Moreover, the results show that the control technique used here could increase the production performance and diminishes the maintenance costs (by avoiding the fluid pound). For future work this adaptive controller should be implemented in the real physical system.

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