Dynamics of Pipeline Pulling Process By Horizontal Directional Drilling

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Abstract. For using in horizontal directional drilling, the authors developed a model of a cyclical pipeline pulling process, enabling to perform calculations of resistance forces of pipeline movement considering the well profile geometry, mass characteristics of drill pipes, pulled pipeline and mud, as well as the velocity parameters of pullback. Analytical dependences were derived to determine absolute values and time changes in pipeline pullback force considering the well geometry, physical properties of interacting elements of the pullback process. In addition, analytical dependences were obtained for certain power consumptions of a drilling rig during pipeline pulling considering the pullback process model.

1. Introduction

In-service pipeline pullback is the most difficult [1] step in horizontal directional drilling (HDD) for construction especially if we speak about a large diameter steel pipeline. A combination of factors determining the features of pullback is reviewed in [3]. Basic approaches to the technological process control are stated in [5]. This article develops the ideas of decreasing the power consumption and other resources used in trenchless construction by pullback control in real time mode.

It is necessary to determine the degree of main parameters influence on the extent of power consumption required for the execution phase by the rig to develop the model of pipeline pullback process. The main controlled parameters are pullback velocity, starting acceleration, execution phase time, pullback process forces [8].

Obviously, instantaneous velocity, acceleration and force of pullback can change in the execution phase process and, eventually, determine the necessary power and time for the execution phase. So, controlling the pipeline pullback process will involve adjusting such parameters as pullback velocity and starting acceleration.

2. Materials and methods

The scheme of pipeline pullback into the borehole is illustrated in figure 1. The total length of the borehole is denoted \( L_{bh} \). The pipeline pullback length – \( L_p \). The length of the pipeline below ground – \( L \). The level difference – \( \Delta H \). The pullback force – \( F_p \). The moving coordinate is denoted \( dx \).

Considering the process recurrence, it is advisable to examine the pipeline movement in one cycle, because cycles will repeat and their number will equal the number of the drill pipes used for borehole drilling[4]. The distance that pipeline overcomes during one cycle and that equals the length of one drill pipe is designated \( l_{dr} \).
In general, every cycle will consist of three periods. Starting the pipeline and drill string and their acceleration to the maximum velocity will be at the first period, the pipeline will move at a steady pace at the second period and braking to a standstill will be at the third. The dependence of the pipeline movement velocity on the distance per cycle would generally look like the one described in illustration (figure 2).

According to the D’Alembert principle, we can state that at every period it will be right for a moving drill string and pipeline in the borehole:

$$\sum F_{\text{act}} + \sum F_{\text{res}} + \sum F_{\text{mom}} = 0,$$

(1)

where $$\sum F_{\text{act}}$$ – the sum of active forces;

$$\sum F_{\text{res}}$$ – the sum of resistance forces of pipeline movement;

$$\sum F_{\text{mom}}$$ – the sum of inertial forces.

Then, for the first period:

$$\sum F_{\text{act}} = F_{\text{rig}},$$

$$\sum F_{\text{res}} = F_{\text{res1}} \left( F_{\text{fr}}, F_{\text{fc}}, F_{\text{fs}}, F_{\text{sfr}} \right),$$

$$\sum F_{\text{mom}} = \left( m_p + m_{d} + m_{c} \right) \frac{d^2x}{dt^2},$$

(2)

where $$F_{\text{rig}}$$ – the pulling force of the drilling rig;

$$F_{\text{res1}}$$ - the movement resistance force at the first period;
$F_{hr}$ - the hydraulic resistance force of the drilling fluid movement in the borehole;
$F_{fcr}$ - the drilling fluid column resistance force;
$F_{fsr}$ - the movement resistance force of the free pipeline segment, located on the day surface;
$m_p$ - the mass of the pipeline;
$m_{ds}$ - the mass of the drill string;
$m_{fc}$ - the mass of the drilling fluid column;
$rac{d^2 x}{dt^2}$ - the acceleration at the first period.

For the second period:

$$\sum F_{act} = F_{rig},$$
$$\sum F_{res} = F_{res,ii}(F_{hr}, F_{fcr}, F_{fsr}, F_{ssr}),$$
$$\sum F_{mom} = 0. \quad (3)$$

So, for the second period:

$$F_{rig} = -F_{res,ii}(F_{hr}, F_{fcr}, F_{fsr}, F_{ssr}). \quad (4)$$

For the third period:

$$\sum F_{act} = 0,$$
$$\sum F_{res} = F_{res,iii}(F_{hr}, F_{fcr}, F_{fsr}, F_{ssr}),$$
$$\sum F_{mom} = (m_p + m_{ds} + m_{fc})\frac{d^2 x}{dt^2}. \quad (5)$$

Then, for the third period:

$$F_{res,iii}(F_{hr}, F_{fcr}, F_{fsr}, F_{ssr}) = -(m_p + m_{ds} + m_{fc})\frac{d^2 x}{dt^2}. \quad (6)$$

During the pipeline pullback process, some part of it stays on the day surface out of well right to the last moment. This part of pipeline is usually located on rollers. We call it the free segment of pipeline. As the pipeline moves, the drilling rig has to overcome the rolling friction force of this free segment. The free segment movement resistance force equals:

$$F_{fsr} = \frac{(L_p - L - x)}{L_p} \cdot m_p \cdot g \cdot k_{rf}, \quad (7)$$

where $L_p$ - the length of the pipeline;
$k_{rf}$ - the rolling friction coefficient of the pipeline;
$L$ - the length of the pipeline section located in the well at the beginning of the cycle;
$g$ - the free fall acceleration;
x - the current coordinate along the well profile.

This component of the movement resistance force is proportional to the mass of the pipeline part located out of the well and the length of which decreases in the course of pipeline headway, therefore, $F_{fsr}$ decreases during pullback.

Thereby, taking into account (7), conclusions contained in [3] and that we analyze the mud shear stress overcoming the resistance force only at the beginning of every cycle, the sum of resistance forces of the pipeline movement on the well on the border of the second and third periods equals:

$$\sum F_{real-iii} = \lambda \cdot \rho_f (L_{bh} - L - x) \cdot \left(\frac{D_{bh}^2 - D_{dr}^2}{8D_{bh}}\right) \left(\frac{dx}{dt}\right)^2 + \frac{(L_p - L - x)}{L_p} \cdot m_p \cdot g \cdot k_{rf} +$$
$$+ \frac{\pi}{4} \left(D_{bh}^2 - D_{dr}^2\right) \sqrt{R_c^2 - x^2 + H_{max} - R_c} \cdot \rho_f \cdot g, \quad (8)$$
where $\lambda$ - the coefficient of hydraulic resistance;
$\rho_f$ - the density of drilling fluid;
$D_{bh}$ – the borehole diameter;
$D_{dr}$ - the drilling rod diameter;
$L_{bh}$ - the borehole length;
$R_c$ - the bending radius of the well profile;
$H_{max}$ - the maximum deepening size of the well profile from the day surface.

Then, deceleration at the third period equals:

$$\frac{d^2x}{dt^2} = -\frac{F_{res.III-III}}{m_p + m_{dr} + m_{fc}},$$

(9)

where $v_{max}$ – the maximum speed of the cycle.

As in equation (8) $\frac{dx}{dt} = v_{max}$, the breaking period length will be:

$$l_{III} = \frac{v_{max}^2}{2 \frac{d^2x}{dt^2}}.$$

(10)

Thus, at the given maximum speed $v_{max}$, the length of the period that may be used for acceleration and further uniform motion is:

$$l_I + l_{II} = l_{ac} - l_{III},$$

(11)

where $l_I$ – the acceleration movement length;
$l_{II}$ – the uniform motion length.

In order to determine the optimum period number in a cycle, let us analyze two different variants of the cycle progress. In the first variant the cycle will have two periods: the acceleration period with even acceleration $a_I$ and length $l_I$ and the breaking period with length $l_{III}$. The uniform movement period is absent in this variant. Then, the dependence of the pipeline movement velocity on the distance per two-period cycle will look like the one described in illustration (figure 3).

![Figure 3](image-url)  
**Figure 3.** The dependence of the pipeline movement velocity on the distance per two-period cycle: I – acceleration period; III – breaking period; $v_{max}$ – maximum cycle speed.

Therefore, acceleration at the acceleration period we will find from:

$$\frac{d^2x}{dt^2} = -\frac{F_{rig} + F_{res.I}}{m_p + m_{dr} + m_{fc}},$$

(12)
And the work to move the pipeline and drill string at the first period:

\[ A_I = \frac{(m_p + m_{ds} + m_{fc})}{2}v_{\text{max}}^2. \]  

(13)

The power needed to move the pipeline:

\[ P_I = \frac{A_I}{t_I}. \]  

(14)

Where the time to pass through the acceleration period will be found from:

\[ t_I = \frac{v_{\text{max}}}{a_I}, \]  

(15)

where \( a_I \) – the acceleration at the first period.

In the second variant the cycle will have three periods: the acceleration period with length \( l_I \), the uniform movement period with length \( l_{II} \) and the breaking period with length \( l_{III} \). Therefore, the dependence of the pipeline movement velocity on the distance per cycle at its different periods in general will look like the one described in illustration (figure 2).

Introducing the uniform movement section, it is necessary to set its length \( l_{II} \), then the acceleration at the acceleration period will be determined as:

\[ \frac{d^2x}{dt^2} = \frac{v_{\text{max}}^2}{2(l_{ds} - l_{II} - l_{III})}. \]  

(16)

Then the work at the acceleration period will be found according to equation (13), and the work done at the uniform movement equals:

\[ A_{II} = l_{II} \cdot \sum F_{\text{res-II-III}}. \]  

(17)

Let us assume that in both variants the pipeline movement before the beginning of the third period will go in equal periods, that is:

\[ t_{II} = t_{I2} + t_{II2}, \]  

(18)

where \( t_{II} \) - the time of passing the acceleration period in the first variant;
\( t_{I2} \) - the time of passing the acceleration period in the second variant;
\( t_{II2} \) - the time of passing the uniform movement period in the second variant.

Then, the saved amount of work will be found from equation (17). And the saved power will equal:

\[ P_e = \frac{l_{II} \cdot \sum F_{\text{res-II-III}}}{t_I + t_{II}}. \]  

(19)

3. Results and Discussion

Now we have the opportunity to analyze the pipeline movement at different working speeds when performing pullback along the entire well profile length. Guided by the abovementioned, it is possible to determine the values of resistance forces that are necessary to overcome at different points of the well profile during pullback, as well as the values of the drilling rig power required for this at different parameters of the pullback process.

The dependences of the pullback resistance forces values on the well profile length in cycles at different maximum working speeds for steel pipelines are described in illustration (figure 4). The dependences are of the same nature and it shows that the pullback resistance forces will have the maximum value at the deepest point of the well profile.
Figure 4. Values of the pullback resistance forces along the well profile length in cycles at maximum working speeds of 5 m/s for steel pipelines: 1 - \( \varnothing 630 \) mm; 2 - \( \varnothing 720 \) mm; 3 - \( \varnothing 820 \) mm; 4 - \( \varnothing 1020 \) mm.

The dependences of the mean power values required to accelerate the drill string in one cycle at different points of the well profile on the position of the pipeline in the well during pullback at different maximum working speeds for a \( \varnothing 1020 \) mm steel pipeline are described at illustration (figure 5). The dependences show that the maximum working speed of the pipeline pullback is one of the most important parameters defining the values of energy consumption to perform the pipeline pullback [7].

Figure 5. Mean power values required to accelerate the drill string in one cycle at different points of the well profile during the pullback process at different maximum working speeds for a \( \varnothing 1020 \) mm steel pipeline: 1- 0.2 m./s, 2- 0.5 m/s.

As in this model the pipeline and the drill string are moving inertially to a standstill after acceleration in each cycle, the obtained power values are sufficient to move the pulled pipeline to a length equal to the length of one drill pipe.

4. Conclusion
The methods presented in this paper allow such dependences to be received and applied to any drilling equipment, various diameters of pipes made of steel and plastics and any working speed of the pipeline pullback process. This can be taken as a basis for pullback process management taking into account dynamic characteristics to minimize power consumption and the most accurate selection of equipment for horizontal directional drilling.
The division of the process model into cycles, each of which corresponds to the movement of the pipeline and the drill string to a length of one drill pipe, is a necessary condition of model's best fit to real construction conditions and allows developing practical recommendations on selecting the pipeline pullback model.

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